



LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

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MASTER'S THESIS

**SYSTEM DYNAMICS MODEL FOR THE MANAGEMENT OF  
CRITICAL RAW MATERIALS IN EUROPE**

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## ABSTRACT

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The high industrial development associated with the population growth requires more access to natural resources. Some of these resources are non-renewable and thus, with the continuous consumption, finite resources might experience depletion and scarcity in future, leading to the risk of supplying the associated materials to global communities. Considering the high importance of some raw materials, EU has established a list of critical raw materials (CRM), based on the assessment methodology that is based on two parameters (supply risk and economic importance). Until now, there are no substantial reserves of most of the CRMs within the EU, and thus, imports of material is important to meet the EU demands.

In this study, the main goal is to present quantitative estimations of CRM's flow in the EU at their different life cycle stages. Given the high complexity of the material life cycles, and the various parameters interacting with the flow of materials, system dynamics methodology is used to model the life cycle of materials in EU. For this purpose, three materials are chosen, Phosphorus (P), Antimony (Sb) and Lithium (Li). The results of the study estimate the amount of material entering the life cycle, material loss, material recycled and material landfilled. Lastly, three scenarios are applied to compare the levels of recycled material in the main stocks in-use. The findings of this study imply that a better management of CRMs at different stages in the EU should be taken into consideration. For the P life cycle, material loss should be seriously considered, and decreasing this loss from the post consumption stages in food is highly recommended. For the Sb life cycle, a better management on the collecting rates, with investing in new technologies for recycling improvement in the lead-acid batteries sector, and other sectors is recommended. For the Li life cycle, Investing in new technologies for improving Li-ion batteries recycling is beneficial to lessen the dependency on imports and extraction.

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## **SYMBOLS AND ABBREVIATIONS**

**CRM** – Critical raw materials

**EU** – European Union

**P** – Phosphorus

**Sb** – Antimony

**Li** – Lithium

**SD** – System dynamics

**CLSC** – Closed loop supply chain

**STPP** – Sodium triphosphates

**MAP** – Mono ammonium phosphates

**DAP** – Di ammonium phosphates

**SP** – Super phosphates

**EOF** – End of life

**EV** – Electric Vehicle

**PET** – Polyethylene terephthalate

**PE** - Polyethylene

**PVC** – Polyvinyl chloride

# 1 INTRODUCTION

## 1.1 Background

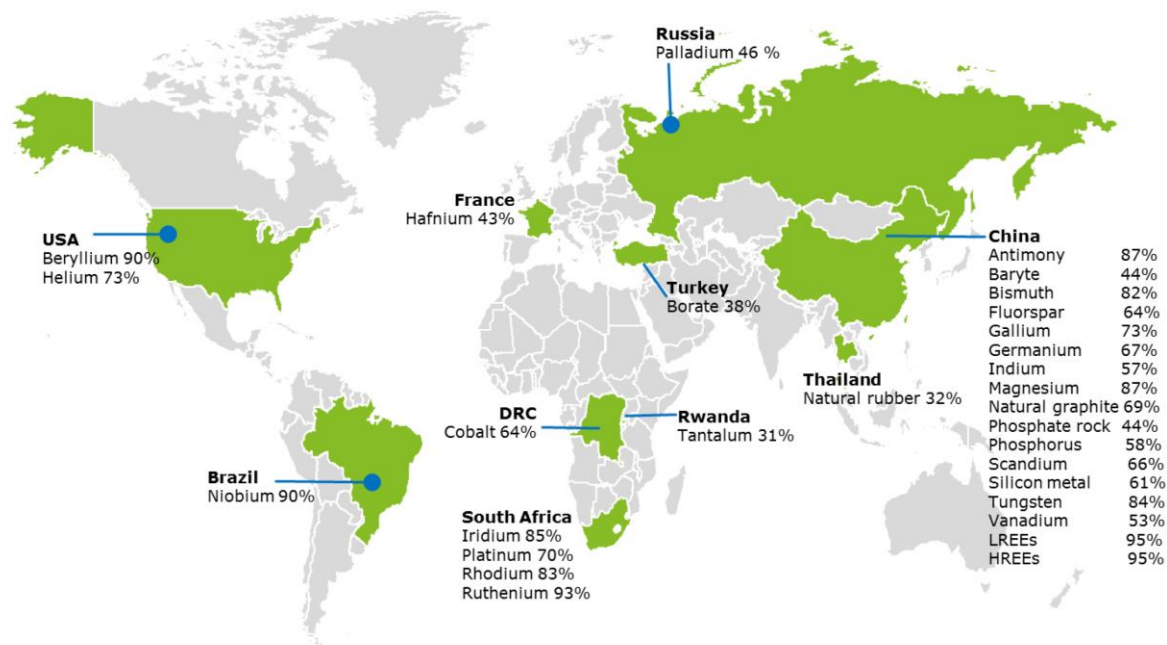
The demand for resources comes in parallel with change in the demographic and lifestyle of global communities. These days, the fast economic and population growth all over the world requires a higher access to material resources to ensure the continuity of life in the global scale. However, the problem arises when some natural resources are nonrenewable, and thus, with the passage of time, the depletion of some resources will cause in the disruption in the supply chain of many products, especially if these resources are not substitutable. This problem has been tackled by many countries, particularly those containing a significant amount of reserves of some nonrenewable natural resources through introducing policies on restricting the exports of these resources outside the country, in order to ensure the local satisfaction of material demand. This, however, affects other countries with no substantial reserves of raw materials, and are primarily dependent on imports of primary materials. Some of these materials, with a very high economic value have been considered as critical materials.

The importance of critical materials these days comes from the several publications done through the European commission, stating their significance in the upcoming years. The development of technologies is opening the door for an increasing access to raw materials, which at some points might exceed the available amount of resources and thus creates the damage to the natural balance (Yanya et al. 2016). On the other hand, the main concern in the concept of raw materials came from the potential risk in providing the supply of materials. This risk associated with the supply of materials is due to the supply disruptions, which comes as a result of the physical shortages of main raw material available resources (Erdmann and Graedel, 2011), especially that the increasing trend of extracting non-renewable natural resources on a continuous basis is leading to the scarcity of resources (Hoogmartend et al. 2016). Hence, the supply risk of raw materials is what global communities are concerned about, and thus leading to the different studies on introducing the concept of critical materials, each with different methodologies and approaches (Restrepo et al. 2017).

There has been no single definition for critical raw materials on a global scale, because each study considers different key aspects, and different scopes as well (Frenzel et al. 2017).

Generally, the supply risk was considered in most reviews and criticality assessment methods for raw materials (Yanya et al. 2016). Considering the continental scope of criticality assessment of raw materials, European Union has been paying high efforts on studies on raw materials and nonrenewable natural resources, especially considering the serious approach from the European Union (EU) to create a sustainable access to raw materials (Pavel et al. 2016). In the Year 2010, the European Union established the very first list of materials to be the critical raw material (CRM) list for the EU (EC- EU commission, 2010). After having a pool of raw materials included in the study, a list of CRM was released based on a two dimensional study including the supply risk and the economic importance of raw materials. EU published several studies after that, including EU commission (2014). The newest publication of the European commission regarding the critical raw materials is in 2017 from which the most updated list of CRM was released (EU Commission, 2017). Figure 1 shows the pool of raw materials assessed under the two dimensions of criticality assessment, supply risk and the economic importance. The more the economic importance of the material, and the more the risk of supply is associated with this material, the more chances to be listed as a critical raw material. The decision is taken based on the thresholds put by the EU for each parameter.





**Figure 1.2 Distribution of the global supply of CRMs.** Percentages represent the share of each country. Source (European Commission, 2017)

The biggest challenge Europe faces is the access to the natural resources because of the lack of reserves of many materials, particularly critical raw materials. From that sense, European communities are dependent on imports of these materials to a high level.

## 1.2 Research questions and objectives

The continuous use of critical raw materials to meet the demand of European population, and the lack of any substantial reserves of CRM within the EU, these two factors pushes Europe to lessen the dependency on extraction of resources which are already limited, and to decrease the rate of imports of CRM to the EU.

Decreasing the dependency on extraction and imports of critical raw materials cannot be done unless a clear, comprehensive and an adequate view of the materials life cycle is introduced, specially the deep knowledge of the flows and stocks that materials undergo, in addition to the consumption behavior of the European communities (Nuss and Blengini, 2018). Decision makers should be able to test the availability for obtaining raw materials from alternative sources, such as scrap, landfill sites, wastewater and others. This study is dedicated to present not only the conceptual model of the materials life cycle, but also the quantitative estimations of the material flow at different life cycle stages. Creating the conceptual model of the lifecycle is essential to discover the pathways of material and thus to investigate the potential

for creating new sources of material. Moreover, the quantitative estimations of material flow have a prominent role in analyzing this potential and providing solid results and managerial implications.

Provided the main objectives of this report, this study is guided by these questions:

***RQ1:*** How much material enters the system?

***RQ2:*** How much material is lost?

These two questions are important to answer to get an overview of the material flow from end to end. they show the efficiency of material usage in the different life cycle stages. In addition, they imply the actual amount of material circulating within the life cycle of materials. After answering these two questions, the focus is shifted to the flow of non-lost material.

***RQ2:*** How much material is recycled?

This question is dedicated to determine the amount of material recycled given the current recycling technologies. It provides an understanding of the trends in recycling for materials in different products sectors.

***RQ3:*** How much material is landfilled?

This question comes as a consequence of the third question. It is formulated in order to demonstrated the recycling efficiencies, and also, to present the potential amount of materials that could be re-used, recycled or reduced given better recycling efficiencies.

***RQ4:*** How much recycled material inside the main stock in-use?

This question comes after answering the 1<sup>st</sup> and the 3<sup>rd</sup> question separately. The importance of this question is considerably high. It is dedicated to show the level of dependence the EU has on imports, extraction and recycling. It shows the current results of the EU management policies for CRMs. In addition, and through providing a scenario-based analysis, the results with current situation can be compared with potential improvements on recycling. The application of the scenarios is done mainly to answer this question under different circumstances and to view the potential of recycling to the material life cycle in EU.

### **1.3 Research methodology**

The research methodology is created in a way to answer the research questions in the first place. There are two methods applied to achieve the main research objectives.

**Table 1.1** Research objectives, research questions and research methods



<b>Research Objectives</b>	<b>Research Questions</b>	<b>Research Methods</b>
Determine the material entering the system	How much material enters the system?	Quantitative Method
Determine the material lost	How much material is lost?	Quantitative Method
Determine the material recycled	How much material is recycled?	Quantitative Method
Determine the material landfilled	How much material is landfilled?	Quantitative Method
Determine the percentage of recycled material in the main stock in-use	How much recycled material inside the main stock in-use?	Quantitative Method

Considering the high complexity of the flow of materials under study, and the complex relationship between the different variables, there is a need to model the materials life cycle in a systematic behavior. System dynamics is used in this study to understand the complexity of the models, show the relationship between the different variables in the models, and to understand the effect of external parameters on the material flow.

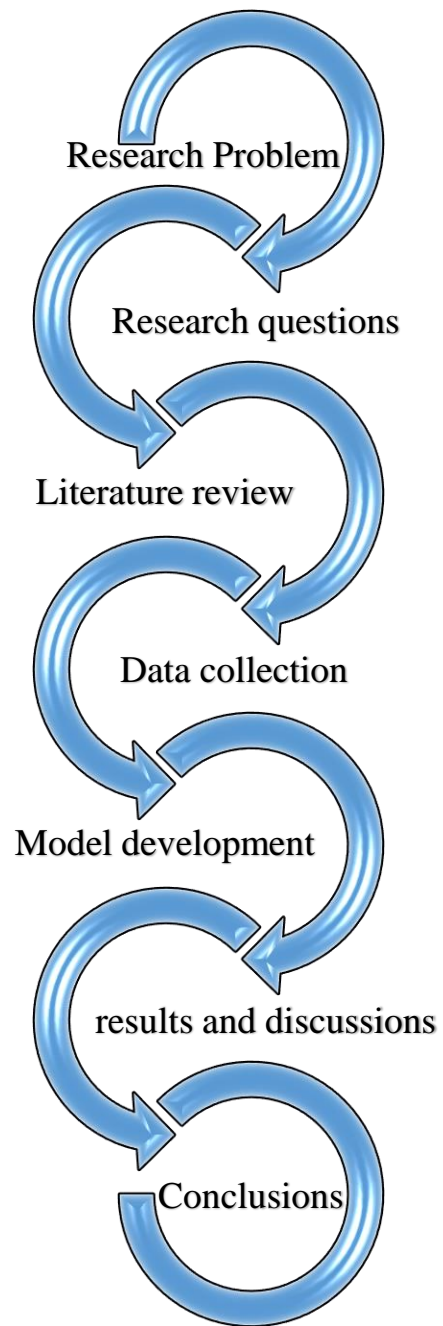
The research design in this study is illustrated based on the research problem in the first place. After defining the scope of the study, and the problem associated with the research, goals and objectives are set and the focus is to achieve these goals. The research questions are created specifically for this purpose particularly. A deep review from past literature and studies is a must step in order to understand the problem and thus, to know the path of the further steps including materials and data collection. Literature review has the ability to identify the trends of research, and the limitations associated with these research (Hypotehses-JAC, 2011). In addition, deep literature analysis on the subsequent processes within the life cycle of materials, starting from mining stage ending up with the last stage. Thanks to this step, the lifecycle of materials can be clearly understood and remodeled. This step is very important to create the conceptual models of the three critical raw materials under study.

Collecting data and information is done subsequently and step by step, to enhance the consistency between data collected and the information available from related studies. The materials flow with different chemical compounds and different forms, thus, these amounts do not represent the pure amount of the materials under our investigation (Phosphorus, Antimony or Lithium). For that reason, the determination process of the pure content of material inside the total amount is done in two subsequent steps.

*1st:* Physical determination of material content. This means that if a traded amount represents an assembled product, where the material is attached physically to it, the content is determined through literature reviews.

*2nd:* Chemical determination of material content. This means that if a traded amount represents a chemical product where the material is chemically alloyed or attached with other materials, the content is determined through calculations by considering the molar mass of the material and the total molar mass of the chemical compound.

Creating the models of materials depends primarily on the material flow, which has been determined in the previous step through the data collection on material life cycle globally and in Europe. At the same time, and due to the external factors affecting the models, and to the interdependencies between different variables of the models, a system dynamics model is applied to understand the effect of these complexities and the interaction between the different variables and parameters, which leads to the dynamic behavior of the whole system. Results are implemented, analyzed and discussed in a way to answer the research questions formulated, and to draw out the conclusions of this research, with further recommendations in the future by other researchers. At some points, part from the product is a chemical compound that contains the desired material, in this situation, the physical determination and chemical determination are done subsequently.



**Figure 1.3 Research design pattern.** Each arrow corresponds to a certain step in the research. The final step ends with “Conclusions” and there are no further steps after that.

## **2 LITERATURE REVIEW**

This chapter is designed to determine the trends of critical raw materials and the motivations behind managing the life cycle of CRMs. Also, it touches the problems associated with tackling the global challenge. This literature review provides an introduction to the methodological approach applied in this research, through providing the related work of previous studies, and concluding the validity of using this method in this study. Finally, an overview on the selected materials (Phosphorus, Antimony and Lithium) is presented, showing the importance of these materials, their supply situation, and eventually their criticality in EU and globally.

### **2.1 Critical raw materials**

In the early definitions of critical materials by the US national research council, the future availability of resources to the global population was a critical aspect for assessing the criticality of raw materials (Keilhacker and Minner, 2017). In addition, and as the world is witnessing the continuous use of finite resources with this rise in population and changes in lifestyles, EU has defined a material to be critical if it is of a high economic importance with a high supply risk (Gardner and Colwill, 2016). On the other hand, the substitution opportunities of a certain raw material also play a role in assessing the criticality of materials, basically through the function or the role this material has (Eggert et al. 2008), because some certain products or technologies are dependent on some substitutable materials (Graedel et al. 2015). The challenge appears when these materials do not have a secure and stable supply situation (Achzet and Helbig, 2013), meaning that if a physical shortage occurs, it might affect the whole supply chain due to the disruptions caused (Bradly, 2014). For this reason, the scarcity of resources has become one of the main global concerns especially for the industrialized intensive countries (Gemechu et al., 2016). For some countries, particularly those members in the EU, tries to tackle the issue of CRM through decreasing the use of some materials in the manufacturing industries. Although this tactic might probably help in the short run, it will significantly affect the competitive level of the EU industries in the end (Rabe et al., 2017). There is to significantly adopt circular economy strategies for tackling the challenges for critical raw materials (Guastad et al., 2017). That is the reason why there has been several calls for providing a sustainable approach for the management of critical raw materials (Mayer and Gleich, 2015).

## **2.2 Sustainability**

Sustainable production is defined by the Lowell center for sustainable production with five main dimensions. Those are, to create goods and services through processes and systems that are non-polluting, to conserve the use of energy and natural resources, to practice of economically viable operations, to maintain a safe and healthy environment for employees, communities and consumers, and last one is to reward socially all working people (Alayon et al., 2017). One of the main ideas of sustainability is to develop a system that meets the needs of present generations without compromising the needs of future generations (Ad J. d Ron, 1998). Natural resources can be an example of what (Ad J. d Ron, 1998) is trying to explain, the system that is providing the needed natural resources for current generation should be able to provide whatever amount is needed by future and upcoming generations without any sort of compromise. Sustainable production ensures the minimization of wastes that comes from the consumptions, in addition, it also ensures the minimization of the use of virgin material and non-renewable natural resources (Martjin et al. 1995).

In order to have a sustainable production, the whole chain of a certain product should be designed according to sustainable requirements (Gungor and Gupta, 1999), starting from the earliest stages ending up with the recovery of the materials. Gungor and Gupta (1999) Goes aside with defining sustainable production, and states that there are two objectives that have been highlighted, the first is to create green products, and the second is to develop new methods for product recovery and waste management, this is actually driven by the fact that many non-renewable raw materials are going through depletion Gungor and Gupta (1999) . Recovery is basically meant for those products that are consumed by the end users, and then they are retaken back for remanufacturing and thus for reuse (Imperatives, 1987), this strategy of recovery would cause a reduction in wastes flowing into landfills and disposals sites Gungor and Gupta (1999). The typical way for enhancing an effective recovery of materials is to close the life cycle and create a closed loop system (Martjin et al., 1995). All these definitions and illustrations mentioned earlier can actually be put more general to cover not only the products, but also the raw materials as well. Although these definitions have been provided on companies' level, they can be explained and implemented on a global scale.

## **2.3 System dynamics**

According to the early definitions by Forrester in 1961, System dynamics is used to understand the behavior of a supply chain. It was Forrester who first illustrated the concept of

SD for modelling a supply chain and went even further by building the supply chain model using system dynamics approach (Forrester, 1997). System dynamics is capable of simulating the effect of random variables in feedback control systems (Boschain, 2012; Golroudbary and Zahraee, 2015). In real life, these variables in addition to other factors might have different relationships with each other, which creates very complicated and complex systems, in this case, system dynamics does have the ability to understand the dynamic behavior of these systems (Faezipour and Ferreira, 2013), and it considers the interdependencies between the factors and variables when simulating the system (Tesfamariam and Lindberg, 2005). System dynamics also takes into account the information feedback and the delays when modelling a certain system (Bhushi and Javalagi, 2004). There has been considerable amount of publications of the use of system dynamics concept in modelling supply chains. Bhushi and Javalagi (2004) for example concludes that the analysis of supply chain management will become stronger through the use of system dynamics thanks to the scenarios that are generated by simulation, which as a result provides information for the modeler. In another paper, Georgiadis (2013) Uses system dynamics approach to model a manufacturing supply chain system, the system they are trying to analyze contains lots of key variables that have different interrelationships with each other, which makes the system extremely complicated and complex. The use of SD however, was capable of analyzing the interactions between the components with giving feedbacks without decomposing the whole system.

Apart from a conventional supply chain, system dynamics has been used in modeling closed loop supply chains as well, there are various publications on implementing system dynamics in different industries and in different aspects, it is capable of modelling a system where there is integration between the production and the recovery systems (Spengler and Schroter, 2003). On the other hand, in Georgiadis (2013), system dynamics was used for the paper industry for the same purpose, but with including different aspects of variables, a model was proposed for closed-loop recycling networks integrating the strategic capacity planning. (Georgiadis and Besiou, 2010) Proposed an SD model for a close-loop supply chain for the electrical and electronic industry taking into account the environmental and the economical dimensions of sustainability, in Georgiadis and Besiou (2008) , the SD concept was used to model a system that tackles recycling activities taking into account the environmental regulations. In this paper, the system dynamics concept is used to model the life cycle of CRMs. The system contains different variables and factors that are interrelated.

## 2.4 Phosphorus

The importance of phosphorus comes from its dominant role towards all living beings, that without it all living beings cannot possibly survive. Currently, there is no such similar material that can substitute Phosphorus with its unique characteristics, particularly in the food production industry (Cordell et al., 2011). Phosphate rock, which is the main source of extractable phosphorus is a non-renewable resource and with time, it's becoming scarcer and more expensive to exploit (Cordell et al., 2011). In fact, there is a fear that the depletion of phosphate rock reserves might considerably occur in the next 50 to 100 years (Cordell et al., 2009). In case of scarcity, the future of the global food security might be affected (Cordell and Neset, 2014). Hence, Phosphorus is globally listed as a critical raw material, for its continuous growing demand and the supply risk related to providing it globally (EU Commission, 2017). From that sense, there has been several studies on phosphorus flow to analyze the flow of the material. Ideally, the best solution for such a problem would be a conservation usage of phosphorus, there are three main possible approaches to conserve the use of phosphorus, and those are to reduce, to recycle and to reuse (Vaccari, 2009). Metson et al (2016) Shows a huge potential for meeting the US annual corn demand by recycling only 37% of US sources of recyclable phosphorus. The growing demand is not the only reason that is leading to such a situation, there is a high inefficiency in the phosphorus supply chain starting from the mining ending up with the consuming stages (Cordell et al., 2009).

Recycling of phosphorus is meant to have a promising result for obtaining phosphorus from alternative results other than resource extraction (Roy, 2017). Phosphorus recycling comes from two main sources, which are the sinks of phosphorus wastes, the municipal solid wastes and the wastewater. As there are advantages, there are also drawbacks of phosphorus recycling, the recycling processes especially from wastewater requires resource demand and continuous treatments, and it causes gaseous emissions to the atmosphere, and the more complex the technology is, the more efficiency the recovery process is, but also the more costs associated will be, and vice versa (Egle et al., 2016). This is mainly because of the very high content of water, accounting for around 98%, which makes it costly to handle and transport (Mateo-Sagasta et al., 2015). The problem in phosphorus recycling, thus, lies under the fact that there is no complete integrated system for such a technology for phosphorus recovery from the waste streams. Meaning that if from one hand the technology has a high efficiency, other factors including economic or environment will be negatively affected on the other hand, which as a result fail to provide the perfect outcome for sustainable use of

phosphorus (Cordell et al., 2011).

## **2.5 Antimony**

Antimony has been listed as one of the critical raw materials by the European commission due to its supply risk, where more than 87% of Antimony supplies come from China. On the other hand, the low concentration of Antimony in the earth's crust, which is about 0.2 g/ton, makes it one of the rarest elements on earth (Othmer, 1992). Globally, the reason behind considering Antimony as a critical raw material is due to the growing need of this material in manufacturing industries, and to the imbalance in the Sb supply chain in the near future (Dupont et al., 2016). Total Antimony mine production accounted for around 160000 tons in the year 2014, where China was the leader producer (Anderson, 2012) reaching around 125000 tons in the same year, where other countries also take place in mining Antimony including Burma, Russia, Bolivia, Tajikistan and others, accounting for 9000, 7000, 5000, 4700 and 8300 tons respectively. The supply chain of Antimony starts from extracting the primary Sb ores, many waste streams then appear throughout the lifecycle stages, starting from mining, occurring as mine tailings, passing through the processing lifecycle stage, where streams occur as process residues, on the manufacturing stage, antimony occurs in the manufacturing scrap as a new waste stream (Dupont et al., 2016). These waste streams are considered industrial residues; the other waste streams come eventually after the usage stage heading to landfills and disposal sites (Dupont et al., 2016).

The recycling of Antimony is limited to the recycling processes of lead-acid batteries in end of life vehicles (Dupont et al., 2016). It can also be observed from copper recycling which contains antimony and lead as heavy metals contaminants (Matsuura et al., 2007). In the case of lead-acid batteries particularly, after the separation of the battery components, recovered lead is used for producing new batteries (Kannan et al., 2010). PVC, which contains antimony, is technically 100% recyclable (Matuschek et al., 2000). Generally, considering the increasing amount of plastic wastes, and its environmental problems that might cause, there is a high concern for global PVC waste recycling (Braun, 2002), because it is the only way that does not have any harmful environmental impacts (Shojai and Bakhshandeh, 2011). PVC wastes are recycled and processed using different techniques and chemical reactions, including addition of heat stabilizers, improvement of thermal stability by filters and others (Shojai and Bakhshandeh, 2011). For PET, to which antimony is also added (Ramamoorthy et al., 2017), some countries follow a deposit refund system like in Sweden (Coelho et al.,



2011). Generally, the common approach is to reprocess PET bottles into PET flakes and pellets, which is considered a closed loop recycling because the recycling process ends up in forming the recycled materials for the aim of manufacturing the same product (Foolmaun and Ramjeawon, 2008). As for Textile recycling, processing recyclable materials is done in order to obtain regenerated fibers to manufacture nonwoven and other materials (Roznev et al, 2011)

## **2.6 Lithium**

Lithium has been listed as a critical material due to the supply risk, associated with the growing importance of this material in the clean energy economy (Cabeza, 2015). The rapid growth of products requiring lithium as main inputs (e.g. electronics and electric vehicles) is leading to the growing demand of resources (Zeng et al., 2014). The distribution of Lithium ores is concentrated in particular regions, where more than 50% of these reserves are located in Chile, and rest are located in China, Argentina, Australia, Portugal, Brazil, United States and Zimbabwe (Hao et al., 2017), with an estimation of 14 megatons to be the global lithium reserves (Jaskula, 2016). The specific feature Lithium has which differentiates from other materials is that it is not only used in traditional products like glass and ceramics, but also it has the potential to be used in next generation products including electrical mobility and energy storages (Martin et al., 2017). Considering the emerge of Electric vehicles into the automotive industry, there has been a demand shift for lithium to include a wider range of products including electric vehicles (Olivetti et al., 2017). The challenge facing global communities is the rapid increase of demand for Lithium, so that the available natural resources in addition to a full efficiency of lithium recovery from wastes cannot meet the future demands in the long run, and therefore the exploration of new reserves is becoming the new trend from which new reserves has been recently discovered (Lu et al., 2017). On the other side, and in order to create a balance in the supply-demand chain, the recycling rates of lithium from post-consumer products should be at least 90% (Zeng and Li, 2013).

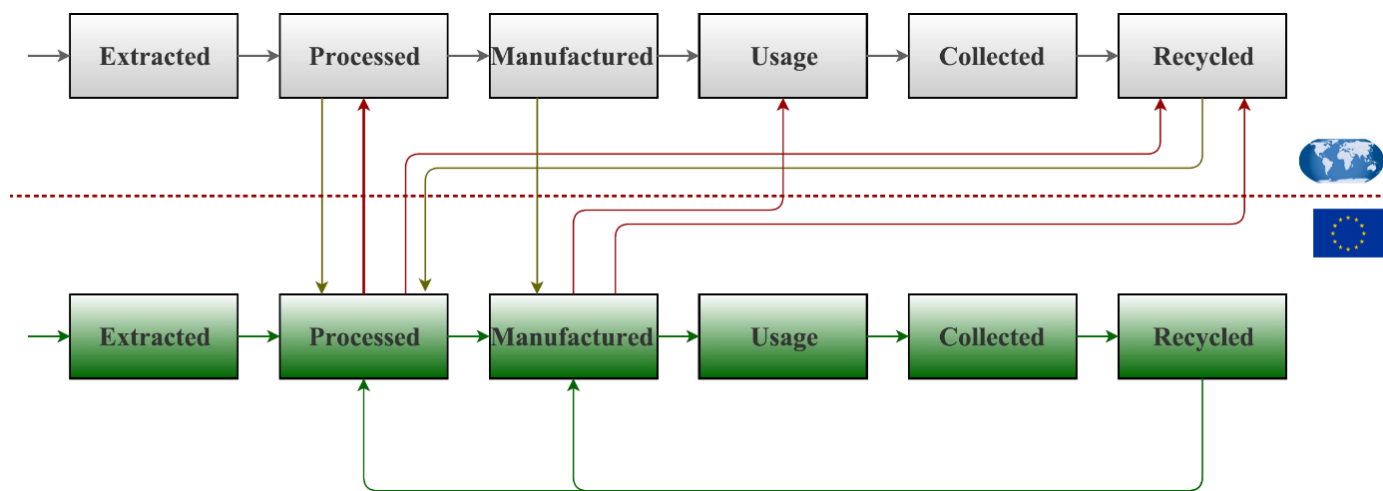
There is a high need for adopting new recycling systems for Lithium and for improving the waste management systems internationally (Sun et al., 2017). The problem in Lithium recycling - Lithium ion batteries in particular - is the increasing lifetime of automotive and thus, the amount of material in the stock in use increases with a small flow of end of life Lithium ion batteries per year (Wang and Wu, 2017). Also, the complex chemical interaction between different metals requires high effort economic and energy wise (Gratz et al., 2014). Even with implemented strategies on Li-ion recycling, recycling is done for the sake of

obtaining other metals including nickel and cobalt, and not Lithium (Wanger, 2011). From an environmental perspective, the recycling of products containing lithium – particularly Li-ion batteries – is important in order to avoid the hazardous results from heavy metals included the post-consumer products, hence the significance behind Lithium recycling comes from not only to conserve resources but to avoid environmental burdens (Ordonez, 2016).

### 3 MATERIALS AND METHODS

#### 3.1 Materials life cycle

The framework to create and model the life cycle of materials in the EU starts by categorizing and separating the whole life cycle into different phases and stages. In the latest reports by European Commission, including the latest publications on establishing the methodologies for critical raw material assessment, the general life cycle of materials is presented as the general guideline. The life cycle of all critical raw materials are applied to this general model (Figure 3.1). In this study, this general model is taken as the basic structure for the material flow and the data collected is done accordingly. The main stages of the model are Mining, Processing, Manufacturing, Usage, Collecting and Recycling.



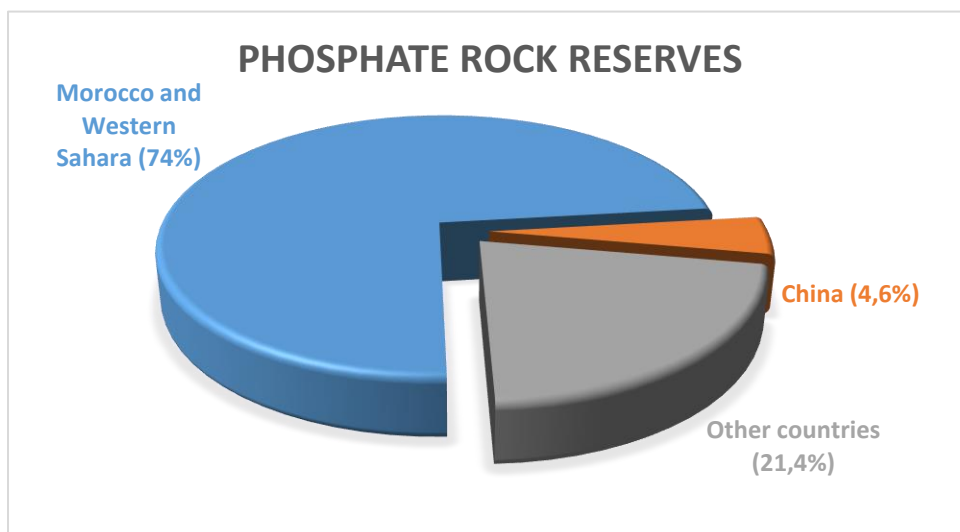
**Figure 3.1 the EU framework of CRM life cycle.** Boxes represent the stocks. Arrows represents the flow of material from one stock to another. The upper life cycle corresponds to the global flow of material, and the lower life cycle corresponds to the EU life cycle. Arrows crossing the borders correspond to the imports and exports of material across the EU borders. Source (EU Commission, 2017)

The creation of the life cycle models of Phosphorus, Antimony and Lithium are done according to the 6 main stages. On the other hand, and for each material separately, other aspects in the life cycle might occur and thus leading to the special model of the material life cycle. Besides literature and related studies and research to the materials under study, data sources was used to quantify the material flow in the previous years, and also it helps to determine the coefficients of the material flow at specific stages in the life cycle. Those data sources include Eurostat (<http://ec.europa.eu/eurostat>), Food and Agriculture Organization of

the United Nations (FAOSTAT) (<http://www.fao.org/faostat/en/>), U.S. Geological Survey (USGS) (<https://www.usgs.gov/>), Trade statistics for international business development (<http://trademap.org/>), The statistics portal (Statista) (<https://www.statista.com/>), World Bank Group (<http://www.worldbank.org/>) and Organization for the Economic Co-operation and Development (OECD) (<http://www.oecd.org/>).

### 3.1.1 Phosphorus

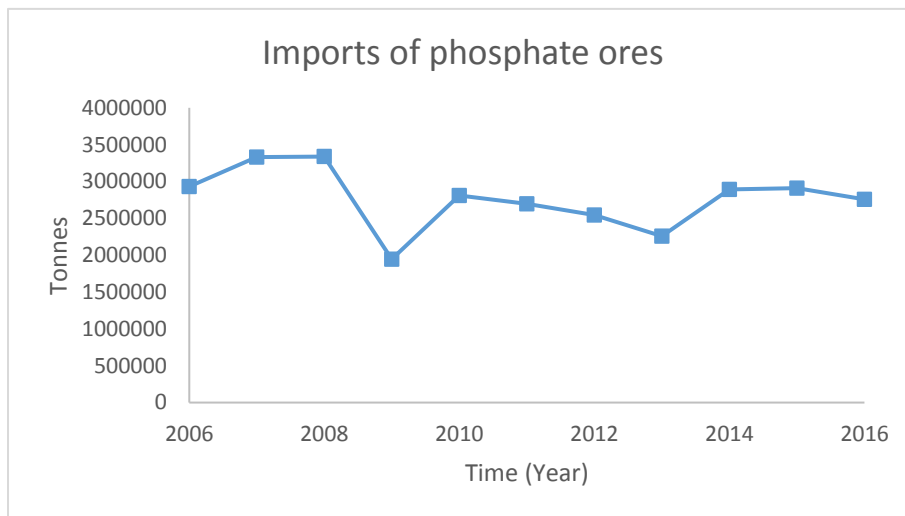
The supply chain of phosphorus is strongly affected by human activities, where more than 90% of phosphorus intakes goes for the agro food production including fertilizers and food additives (Scholz and Wellmer, 2015). Sattari et al (2012) and Kleemann & Morse (2015) shows that the supply chain contains lots of inefficiencies contributing to a big loss of phosphorus before reaching the consumers. The distribution of phosphate rock reserves is very limited to particular regions, where around 74% of the global reserves are located in Morocco and the western Sahara (Figure 3.2)



**Figure 3.2 Global distribution of Phosphate rock reserves.** Percentages represent the share of each country of the global known reserves. Data Source (Jasinski, 2017)

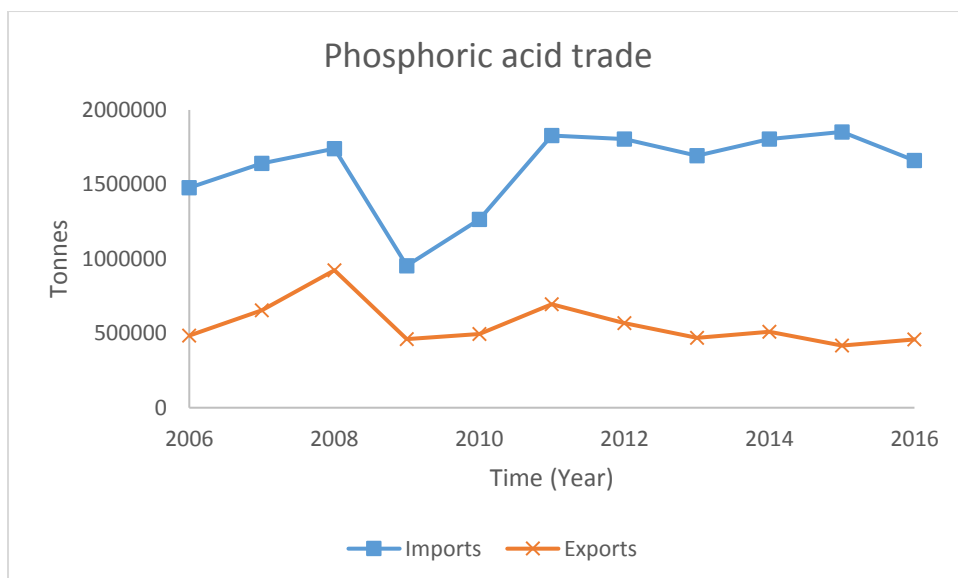
The first stage, which is the supply of raw materials correspond to the mining of phosphate ores (Figure 3.6 – F1), and then processing the virgin material into phosphoric acid through reacting the phosphate rock with sulfuric acid (Straaten, 2002; Kratz and Schung, 2006). The trade of primary material can be seen in Figure 3.3 representing the imports of Apatite to the European Union. The general trend of the imports activity is stable and is neither increasing nor decreasing, except for the year 2009, which experiences a slight decrease due to the

global economic crisis, from which it recovers in the subsequent years. There are no significant exports from the EU to countries outside the union; the main reason is due to the lack of any substantial reserves of phosphate rock. The only available reserves space is in Finland, where around 65000 tonnes P is extracted for further usage in the agricultural sector.



**Figure 3.3 Imports of phosphate ores to the EU between 2006 and 2010.** Data Source (Trademap, 2017)

The processing of primary phosphorus (Figure 3.6 – F2) takes place after mining the primary materials. This stage corresponds to the processing of the virgin material into phosphoric acid through reacting the phosphate rock with sulfuric acid (Straaten, 2002; Kratz and Schung, 2006). This results in the production of phosphoric acid. This process is a pre-manufacturing step after the mining and beneficiating process of primary phosphorus; the aim of this process is obtain phosphorus with acceptable concentrations that can be industrially utilized. For the EU, the imports of phosphoric acid is always more than the exports (figure 3.4), at least for the past ten years (2006-2016). Like other trading activities, the year 2009 is the only year that material traded experience sharp changes.

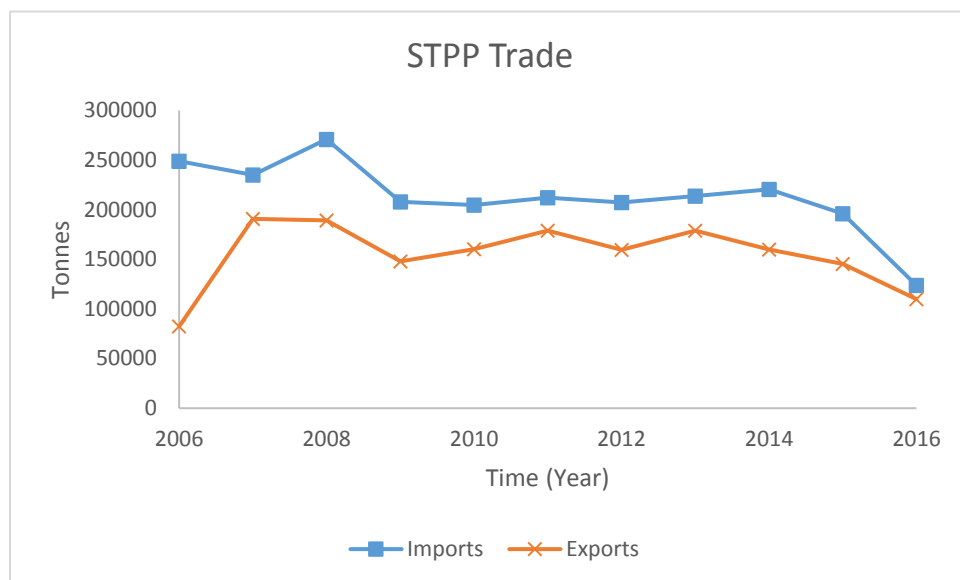


**Figure 3.4 Trade of Phosphoric acid for the EU between 2006 and 2010.** The blue line with solid mark (■) represents the imports to the EU. The red line with solid mark (×) represents the exports from the EU. Source: (Trademap, 2017)

After processing of phosphorus, the chain is separated into different sectors (Figure 3.6 – F3), where agriculture, food additives and detergent builders are the main sectors that phosphorus flows to, corresponding to the manufacturing stage at the supply chain. In the agriculture sector, phosphorus flow follows a chain starting from fertilizer production in the form of MAP, DAP and SP, then crop production, agro-commodities, food and human consumption, at each level, there exists sub waste generations and recycling (Straaten, 2002). In food additives sector, phosphorus chain is in the form of sodium triphosphates and other polyphosphates derived from phosphoric acid (Oliveira et al., 2011), it is used as a preservative for different categories of food including Meat preparations, cheese products, vegetables, fruits and different kind of beverages (Ritz et al., 2012). Also, phosphorus is used in feed sector for the livestock consumption. The other sector that phosphorus flows into is the detergent industry, where phosphorus is used in the form of STPP as a detergent builder to soften the wash water (Morse et al., 1995). The use of phosphorus in this sector particularly has been in a lot of arguments to ensure the safety of detergents to the waterbodies.

In the EU, policies were introduced to limit the use of phosphorus in detergents due to its harmful effects for water. The high mobility of phosphorus in detergents, and thus in water after detergent consumption makes it hard to recover in the post consumption stages, in which the excess presence of remained phosphorus in waterbodies will cause eutrophication

(Fowdar et al., 2017). As per the figure 3.5, both the imports and the exports of STPP have been comparatively stable until the year 2014 where both experienced a decreasing trend until the year 2016. The decreasing trend of STPP exports can be explained based on the fact that STPP production is decreasing because of limitations and restrictions on STPP usage in laundry detergents. The same reason can be applied on the trend behavior of the imports. In the future, the expectations are that the production and the trade of STPP will occur for the purpose of providing phosphate based food additives in the food processing sector.



**Figure 3.5 Trade of Sodium Triphosphates (STPP) for the EU between 2006 and 2010.** The blue line with solid mark (■) represents the imports to the EU. The red line with solid mark (×) represents the exports from the EU. Data Source (Trademap, 2017)

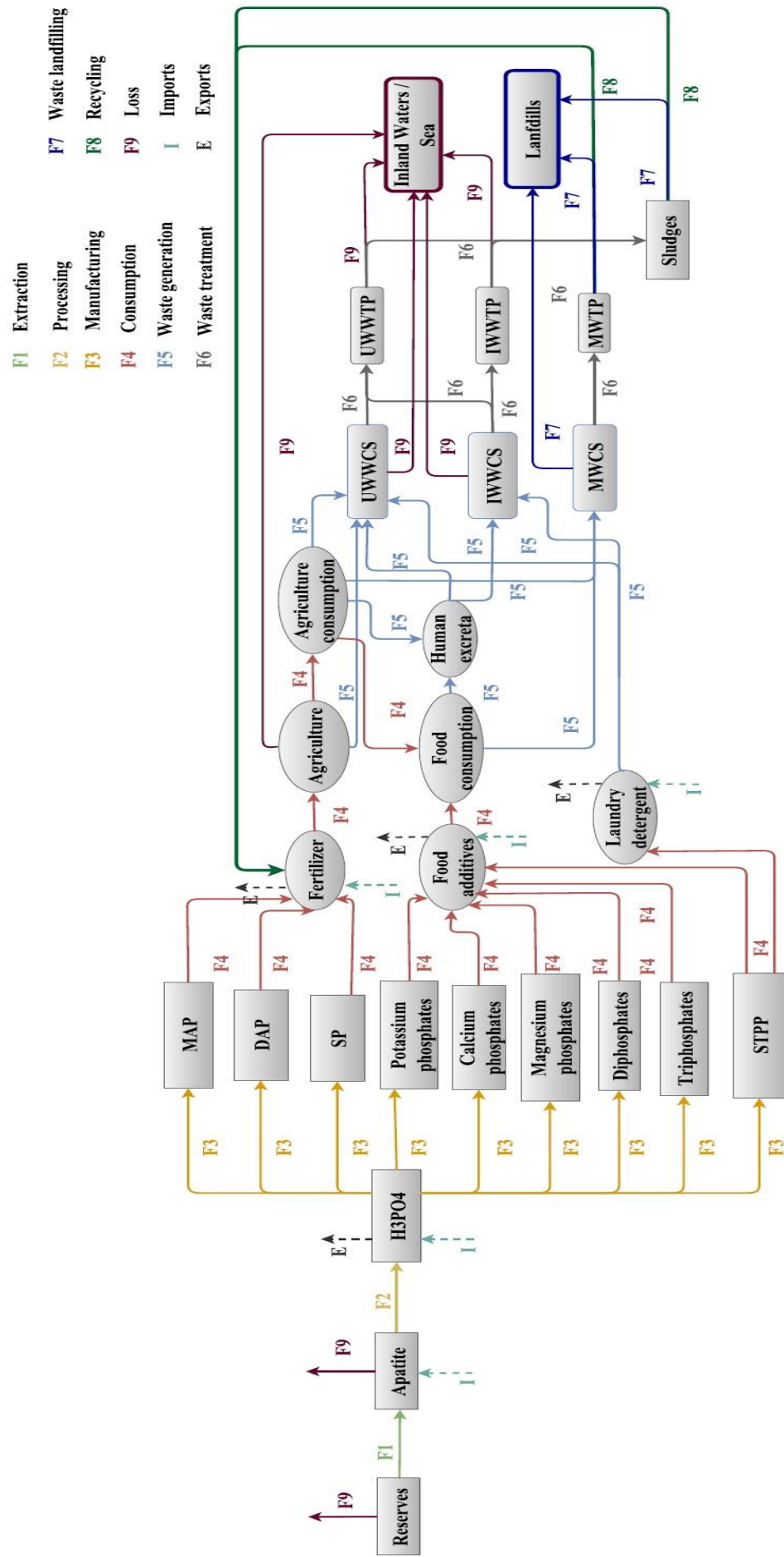
The consumption stage in the phosphorus life cycle (Figure 3.6 – F4), corresponds to the application of phosphate fertilizers to soil, which contributes primarily to crop production. In this sector, the crop production is basically the main driver for fertilizer application to the soil. In the European Union, there has been not much difference in the fertilizer consumption between the years 2002 and 2014, where around 163 Kg/ha was consumed between these years. Also, and based on a study by (Schoumans et al., 2015), the amount of fertilizers consumed per one hectare of arable land was 7 Kg P<sub>2</sub>O<sub>5</sub>/ha. In the food additives sector, the amount of phosphorus added to processed food depends primarily on the EU policies and restrictions. Based on the European food safety authority (EFSA), the average amount of phosphorus that can be added to processed food is 2000 mg P<sub>2</sub>O<sub>5</sub>/Kg of food.

The post consumption stages start with waste generation at different levels (Figure 3.6 – F5).

Among the food generated from crops and animal sources, a significant amount of this food is lost prior to the actual human consumption, this is particularly a significant deficiency not only in the phosphorus life cycle but also in the food supply chain. In this sector, human activities in the EU are among the top contributors to food wastes with around 53% of the total waste generated (Stenmarck et al., 2016). On the other hand, and after the consumption of food by the population, wastes are in the form of human excreta including urine and feces. In another phase of waste generation, the usage of laundry detergents by households contributes to the P waste generation through the flow of STPP into wastewater prior to the collection stage which occurs through implementing wastewater collecting systems. These wastewater collecting systems are designed to collect wastewater primarily from the household sources. In Europe, and according to the European environment agency (EEA), around 0.7% of wastewater is not collected, reflecting a high collecting efficiency for wastewater generated.

After wastes are collected, recycling processes take place for each waste stream. For the wastewater, there are special treating systems where collected wastewater goes to the wastewater treatment plants. In these plants, wastewater (including household and human excreta wastes) is treated (Figure 3.6 – F6). For wastewater stream, In Europe particularly, the wastewater treatment percentage ranges between different countries, OECD presents the percentages for 7 different EU countries which are Slovakia, Ireland, Denmark, Estonia, Luxembourg, Poland and Latvia, with wastewater treatment percentage reaching to 64%, 65%, 91%, 82%, 98%, 71% and 77% respectively, leading to an average of 79.5%. These treatment processes take place prior to the P recycling from wastewater. There are 6 different paths for the sludge produced from urban wastewater, those are agriculture, landfill, incineration, compost and other applications, dumped to seawater, and lastly other applications. Before heading to those paths, produced sludge, is disposed in disposal sites, with a disposing percentage of 87%, as an average. According to Eurostat waste database, the amount of sludge heading for agriculture use represents around 27.6% from the total disposed sludge, whereas 36.4% goes for incineration, 14% to landfills, 23.3% for composting, 9.6% for other applications and a very negligible amount of sludge is dumped into the sea. For the solid waste stream, the percentage of the solid wastes recycled is 44%, whereas those wastes heading to landfills represent as an average around 25% of the total waste collected at the same year, and the rest 31% goes for other streams including incineration, based on data from the Eurostat.





**Figure 3.6 Phosphorus life cycle in EU.** Boxes represent the stocks of material prior to usage. Circle represent the stocks of material in post consumption stages. Arrows represent the flow of material. dashed arrows represent the imports and export of material

### 3.1.2 Antimony

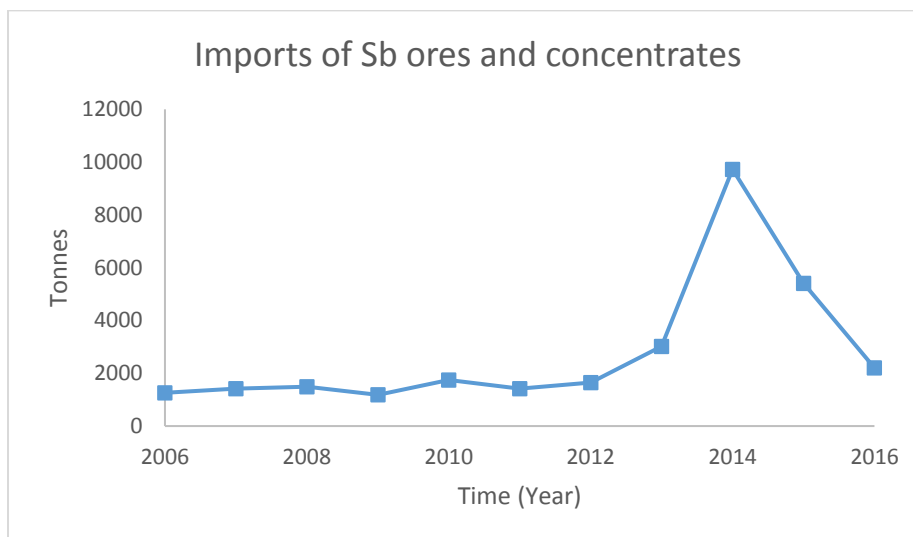
Globally, there are around 42 sources of primary antimony minerals, The antimony ores from which antimony material is extracted contains around 1 to 10% of Sb in the form of  $\text{Sb}_2\text{S}_3$  (Krenev et al., 2016). The total mine production of Antimony accounted for 167000 tonnes and 169000 tonnes in 2010 and 2011 respectively, with total world reserves accounting for 1.8 Mt (Carlin, 2012). China was and still the leader producer of primary Antimony with 150 kt in 2011, with total reserves around 950000 tonnes of Sb (Carlin, 2012). Sb ores reserves are distributed in different countries, where China has the most of these reserves (35%) (Figure 3.7).



**Figure 3.7 Global distribution of Antimony ores and concentrates.** Percentages represent the share of each country of the global known reserves. Data Source (Guberman, 2017)

The primary phases for obtaining antimony comes from stibnite ore, this one is currently the primary source for antimony production worldwide (Dupont and Binnemans, 2017). Although the reserves are distributed a similar between the three countries, China, Russia and Bolivia, more than half of the primary production of Sb is done in China, with more than 57.4% of the global production (Dupont and Binnemans, 2017). Europe in particular does not have any mining activities for primary Antimony, and thus, it totally relies on imports from outside the region. For that reason, EU is primarily dependent on the imports of primary Sb to

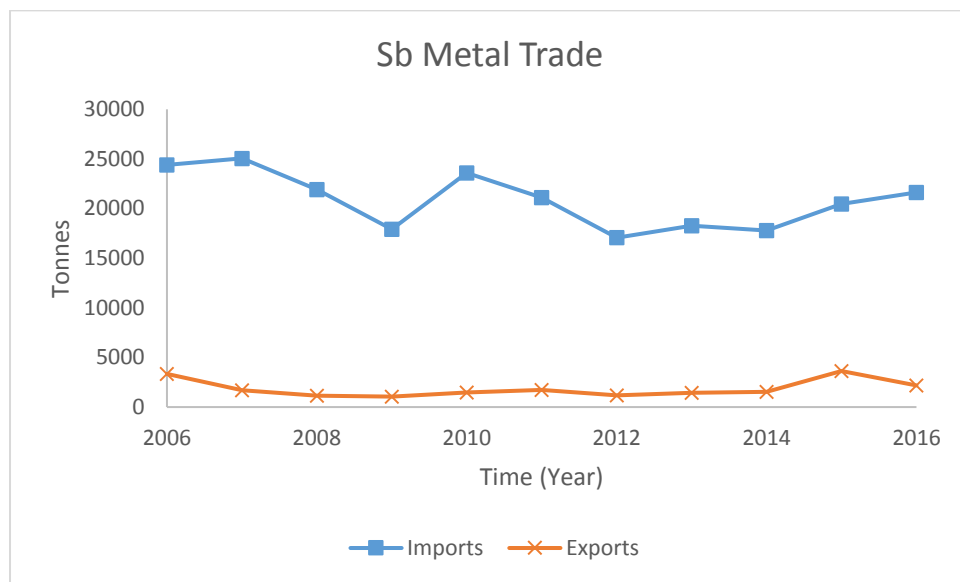
satisfy the local demand of the European communities. The average amount of Sb ores imports to the EU is 2078 tonnes (figure 3.8), excluding the sharp increase in the year 2014 which accounted for 9727 tonnes of Sb ores imported. For the past ten years from 2006 till 2016, the trade has been almost stable. Although the trend experiences a sharp increase in 2014, the amount of imports recovers to the previous trend as it reaches 2016. These details are important to define the mathematical formulation of the ores imports to the EU region, considering its sensitive effect overall system and the dynamic behavior of the Sb life cycle in the EU.



**Figure 3.8 Imports of Sb ores and concentrates for the EU in duration between 2006 and 2010.** The blue line with solid mark (■) represents the imports to the EU. Data Source (Trademap, 2017)

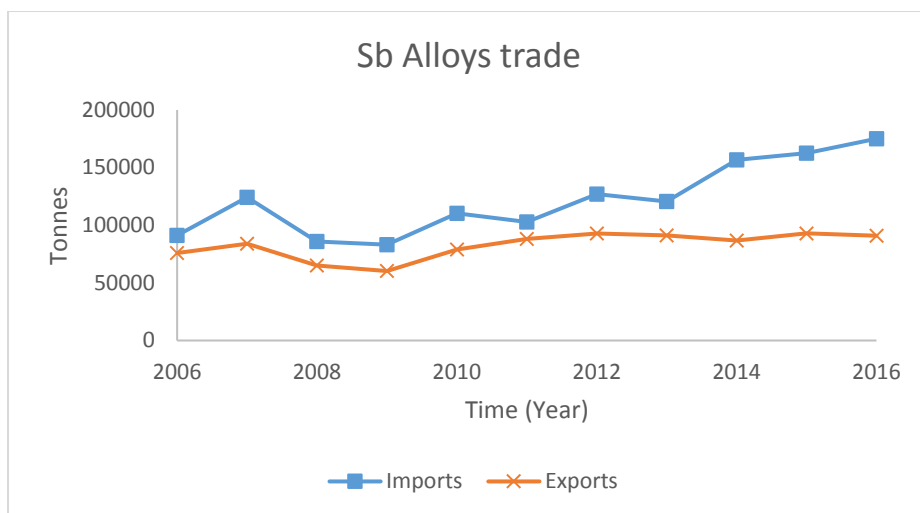
In the processing lifecycle stage (Figure 3.12 – F1), leader producers around the globe, reaching a total plant capacity up to 138300 tonne/yr of Sb content, dominate the refining processes of antimony minerals. From which 3 companies, Mines de la lucette, Societe Industrielle et Chimique de L’Aisne (France) and Union Minière (Belgium) are european, contributing to Sb metal and Sb oxides production with maximum capacities reaching to 9500, 12000 & 6000 Sb tonne/yr respectively (Anderson, 2012). Antimony trioxide, or  $\text{Sb}_2\text{O}_3$ , which is one of the refined forms of primary antimony is the most important product that is commercially utilized, and it is added to different products a flame retarding agent. Antimony Trioxide can be considered as a semi-finished product resulting from the volatilization of antimony metal (Anderson, 2012)

In case of Sb metals, the European market relies heavily on imports with a comparatively less amounts of exports per year. This balance in the European trade for Sb metal reflects the EU dependency on Sb not only as a raw material, but also as a processed material that goes further into the manufacturing sector. In the figure 3.9, the dependency on processed Sb imports to the EU can be seen as the imports are higher than the exports by an average of 30000 tonnes of Sb metal in the past ten years. The trend of both flows (Imports and exports) is comparatively the same and is stable, except for minor changes in imports in the year 2009 due to the global economic crises.



**Figure 3.9 Trade of Sb Metal for the EU in duration between 2006 and 2010.** The blue line with solid mark (■) represents the imports to the EU. The red line with solid mark (×) represents the exports from the EU. Data Source (Trademap, 2017)

The European Trade of Sb Alloys is shown in Figure 3.10. The decline in the years 2008 and 2009 in both imports and exports are due to the global economic crisis, and thus, this change in the trend cannot be considered a normal behavior. The European market imports more Sb alloys than exporting, at least for the past ten years as can be shown clearly, with even a growing trend in the imports.

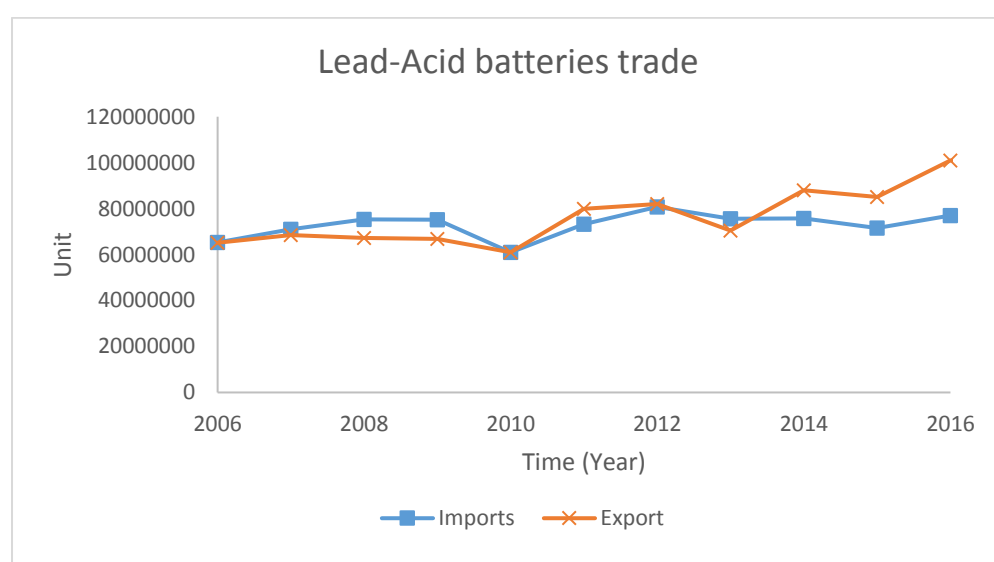


**Figure 3.10 Trade of Sb Alloys for the EU in duration between 2006 and 2010.** The blue line with solid mark (■) represents the imports to the EU. The red line with solid mark (×) represents the exports from the EU. Data Source (Trademap, 2017)

In the manufacturing stage (Figure 3.12 – F1), Antimony is used for different purposes, but mainly as a flame retardant. The major use of Antimony is as a flame retardant in clothes, toys and plastic products (Gutknecht, 2015). As for the Antimony content, PE contains from 8 to 16% of  $\text{Sb}_2\text{O}_3$ , whereas PVC contains from 1 to 10% of  $\text{Sb}_2\text{O}_3$ . According to the International Antimony Association (I2a), Sb content in PET ranges from 150 to 250 mg/Kg, where Antimony is added in the form of Antimony trioxide ( $\text{Sb}_2\text{O}_3$ ) (Krenev et al., 2016). For the electrical and electronic equipment sector, the global consumption of Antimony metal accounts for around 65000 tons per year, accounting for around 50% of the total production (Beukens and Yang, 2014). PET, which antimony is also included in it, is used in the textile industry as well (Ramamoorthy et al., 2017). Antimony is also used in the electronics and electric equipment industry as a flame retardant, where personal computers contain around 0.01% of antimony, mainly antimony oxides (Five winds, 2001). In another phase of Antimony demand products, Antimony is included in the manufacturing of textiles through the application of antimony trioxides in the manufacturing process (Baker and Ghanem, 2014). In addition to the portable phones, where 0.1% of a mobile phone goes for Sb (Navazo et al., 2014).

In Europe, Antimony is basically used in manufacturing batteries, PET containers, PVC, electric & electronic equipment, textiles, wire and cables and other products, at which around 59% goes for the batteries manufacturing, and the rest goes in the flame retardants sector, including PE containers, textiles and electronics. Lead-acid batteries are well known for their

high market share among all other types of batteries, and they are used primarily in the automotive industry, in addition to other sectors including power back-up systems and stationary applications (Amborse et al., 2014). The trade of lead-acid batteries is shown in Figure 3.11. The average units of batteries imported to the EU is around 70 million units whereas the average units exported from the EU is 76 million units. The difference between the imports and the exports reflects the European activities in producing lead-acid batteries for exporting purposes. It is important to note down that this amount of traded units is the actual amount and not those included in the other products including vehicles, keeping in mind that the most use of lead-acid batteries goes to the automotive industries for different types of vehicles.

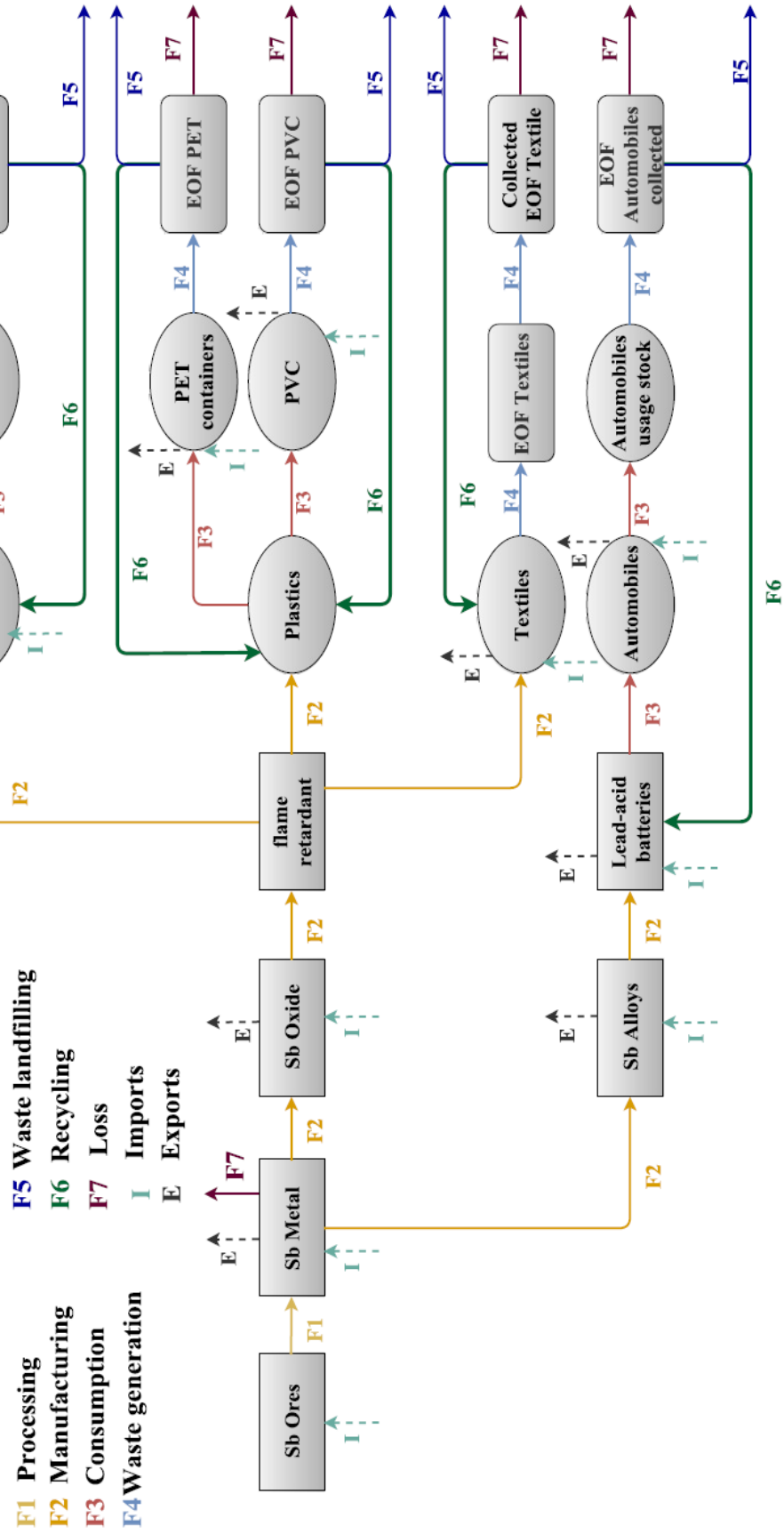


**Figure 3.11 Trade of Lead-Acid batteries for the EU in duration between 2006 and 2010.** The blue line with solid mark (■) represents the imports to the EU. The red line with solid mark (×) represents the exports from the EU. Data Source (Trademap, 2017)

The manufacturing of PET and PVC occupy around 17.2% of the total plastics application in Europe, at which PET applications account for around 7.1%, and PVC applications around 10.1% from the total plastic materials applications in EU (Europe, P., 2010). The demand of PVC has reached its peak in 2007, at which it reached 6.6 million tonnes, when it started decreasing reaching a demand level below the peak by 25% in 2015. The EU trade of PET in primary forms has been continuously growing from 2006 to 2016 with a slight increase rate per year. The average amount of imports is 2.65 million tonnes of PET compared with average exports of 2.18 million tonnes.

In consumption life cycle stage (Figure 3.12 – F3), the consumption distribution in Europe is different from the global consumption. The majority of Sb goes for batteries sector mainly as lead-acid batteries, accounting for around 47% of the total consumption, and then 35% for electrical & electronic equipment, 8% for textiles, 6% for wire and cable and the rest (3%) goes for other uses. Antimony is consumed and used in flame retardants, transportation batteries, chemicals, ceramics and glass, distributed as 72%, 10%, 10% and 4% respectively, where the rest 10% goes for other sectors (Krenev et al., 2016).

The recycling of antimony (Figure 3.12 – F1) is typically done from spent lead-acid batteries, where in US for example, antimony recycling from spent batteries is the prominent source for obtaining secondary Sb (Gutknecht et al., 2014). In the recycling life cycle stage, and for Lead-acid batteries recycling in particular, end of life batteries are carried out to regional battery recycling stations, at which lead alloys are smelted, and then secondary lead with antimony scrap is sent for LA battery manufacturers (Carlin, 2006). Throughout the recycling process, different technologies are applied, namely the pyro metallurgy and hydrometallurgy. However, the physical separation of spent lead-acid batteries always occurs in order to obtain the different parts that were physically assembled in the battery package (Sun et al., 2017). Based on Eurostat sources on spent batteries generated annually, around 90% of those batteries are being collected for further operations. From those collected batteries, particularly spent lead-acid batteries, around 65% of them are being recycled and remanufactured into the same product through secondary material, to be further used by the industries as batteries for motor vehicles, energy storage systems and power back-ups. In the Automotive industry, the amount of vehicles at their end-of-life stages reached around 6 million units in the year 2015, from which around 87.1% was totally recycled and reused, including their assembled parts (i.e. batteries), based on Eurostat database on end-of-life vehicles and the recovery options by the European facilities.

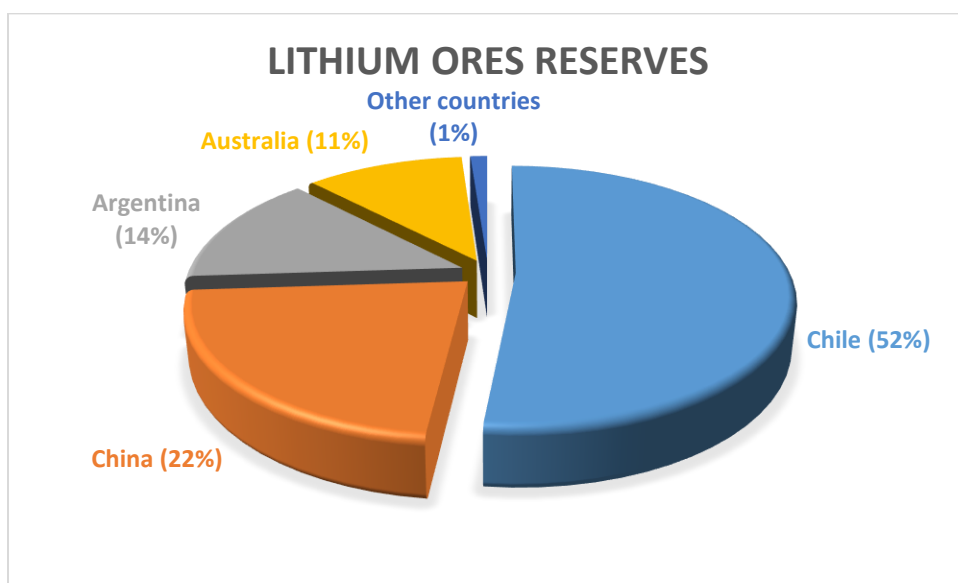


**Figure 3.12 Antimony life cycle in EU.** Boxes represent the stocks of material prior to usage. Circle represent stocks of material during the usage. Arrowed boxes represent the stocks of material in post consumption stages. Arrows represent the flow of material. dashed arrows represent the imports and export of material



### 3.1.3 Lithium

There are multiple sources for obtaining Lithium from the environment, including lithium ores and concentrates, brines and clays (Sverdrup, 2016), where among the Lithium ores spodumene, lepidolite and petalite are the three main sources (Sun et al., 2017). Chile contains more than half of the global Li ores reserves with around 52% of the total reserves. Then comes China, Argentina and Australia, where the other left reserves which account for less than 1% are distributed in other countries. (Figure 3.13)

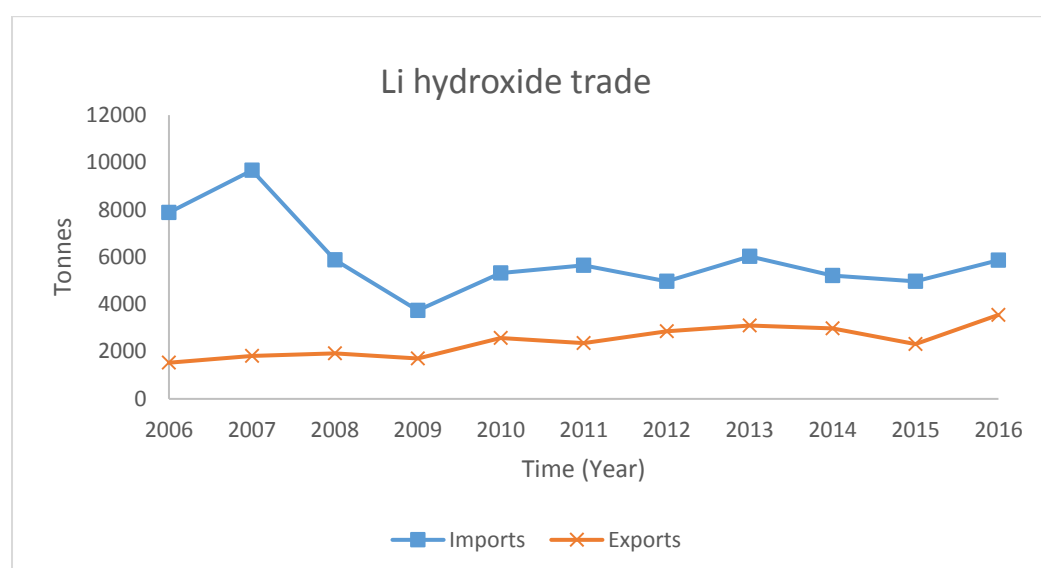


**Figure 3.13 Global distribution of Antimony ores and concentrates.** Percentages represent the share of each country of the global known reserves. (Data Source: Jaskula, 2017)

The mining production of Lithium ores in EU occurs from Lepidolite (Figure 3.16 – F1), whereas the significant amount of primary lithium comes from imports outside the region. After the mining stage, the primary Lithium obtained from different ore sources are processed into various of chemical products, the major processed chemicals are in the form of lithium carbonates, lithium oxides, lithium bromides, lithium chlorides, lithium metals and Butyllithium (Jaskula, 2017).

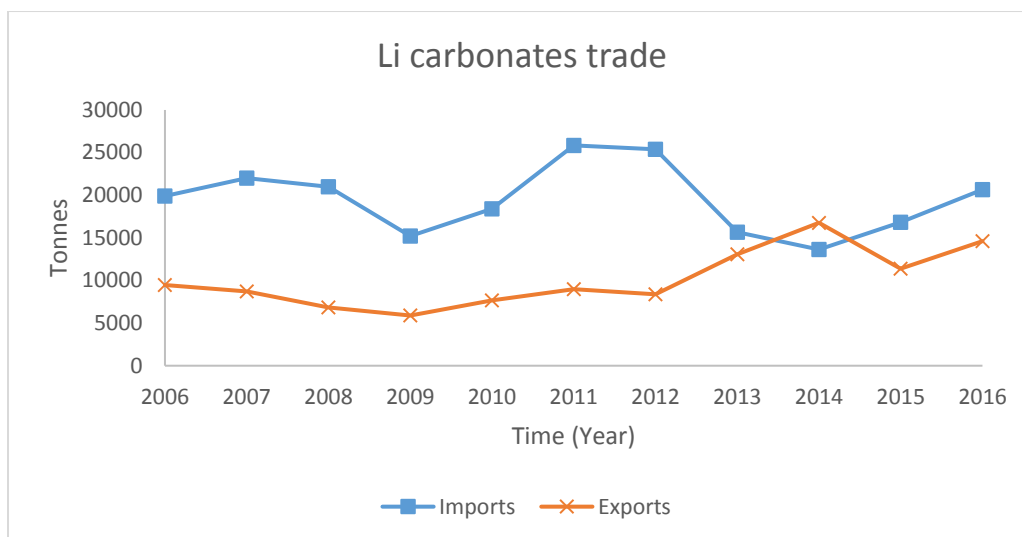
Prior to the end products or the major applications, the extracted Lithium undergoes processing stages (Figure 3.16 – F2) from which Lithium products are obtained, including Lithium concentrates, Lithium hydroxide, Lithium chloride, Lithium carbonate (Yaksic and

Tilton, 2009). In the EU, the trade of lithium in the processed forms can be seen in figure 3.14. For Lithium hydroxides, the imports of material exceed the exports with different levels. The imports and exports experience a decrease at the year 2009 due to the economic crisis.



**Figure 3.14 Trade of Lithium Hydroxides for the EU in duration between 2006 and 2010.** The blue line with solid mark (■) represents the imports to the EU. The red line with solid mark (×) represents the exports from the EU. (Source: Trademap, 2017)

Figure 3.15 shows the imports and the exports of lithium carbonates separately. Although the exports of Li carbonates exceed the imports at the year 2014, the overall trend of the imports is still higher for the past ten years. The average amount of Li carbonates imports is 16000 tonnes of Li carbonates, whereas the average amount of exports of the same product is around 9000 tonnes of the same product. The trade of the two processed materials is equally important, especially the significance of these types of materials in further manufacturing especially for the Li-ion batteries which is on the rise.



**Figure 3.15 Trade of Lithium Carbonate for the EU in duration between 2006 and 2010.**

The blue line with solid mark (■) represents the imports to the EU. The red line with solid mark (×) represents the exports from the EU. (Source: Trademap, 2017)

Each of the processed chemicals contribute to the manufacturing of products for end users (Figure 3.16 – F3). Traditionally, lithium has been used in glass, ceramics and lubricating greases, with the advancement of technology, the uses of lithium got spread into high-tech industries (Hien-Dinh et al., 2015). The major use of Lithium is in lithium ion batteries and glass and ceramics. The main uses of Lithium mainly are distributed to 11 different products, where the major amount of Lithium goes for batteries manufacturing, in addition to other products including lubricating greases, glass, polymers, aluminum, and others (Ziemann et al., 2012). Lithium-ion batteries is mainly used in three main sectors, Electric vehicles, consumer electronics and energy storage systems (Hao et al., 2017). Among the components that Li-ion batteries consist of, there are active materials in the cathode and the anode, accounting for around 20% and 10% of the total battery pack respectively (Romare and Dahlof, 2017). The global leaders of Lithium ion battery manufacturers are Panasonic Sanyo, BYD, LG Chem, Samsung, Wanxiang, GS Yuasa and Lishen with market share of 33, 18, 17, 9, 5, 3 and 3% respectively (Statista, 2017). There are other uses of lithium in pharmaceutical products, aluminum smelting, steel casting, plastics production and cement production. In this study, and due to the data limitation, the flow of lithium into sectors other than batteries and glass sectors goes to unknown sinks and are considered loss. The focus is thus on the flow of lithium in lithium-ion batteries supply chains. The amount of lithium inside the Li-ion batteries comes primarily from lithium carbonates in addition to lithium hydroxide as a secondary source for the manufacturing process of batteries. As for glass and ceramics

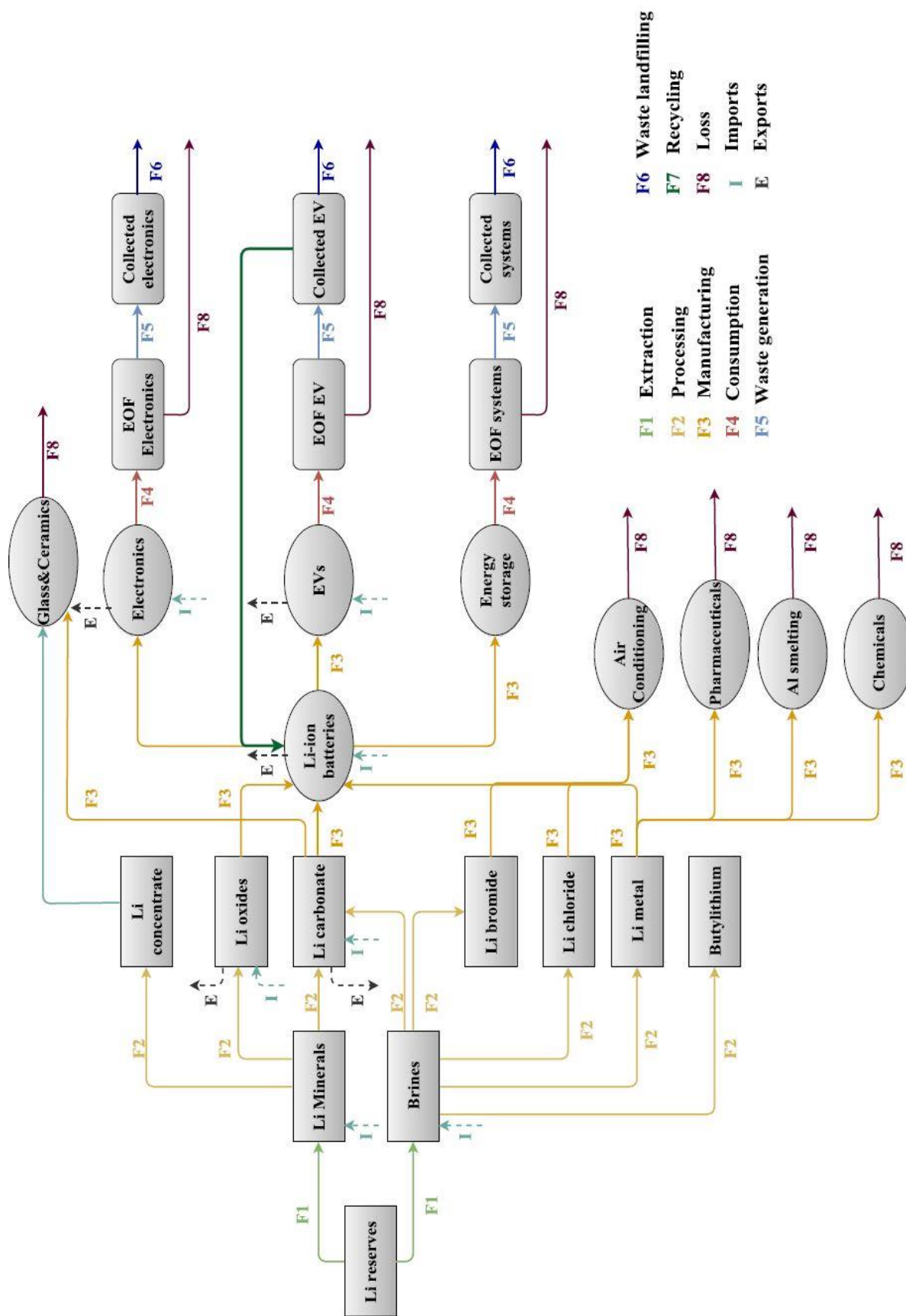
production, Lithium hydroxide is the major element among other lithium derivatives that are added to this sector, in addition to lithium concentrates without further processing. The other uses of lithium derivatives go for other products processing such as aluminum smelting, steel casting and others. Whereas other derivatives flow into the pharmaceutical industry and polymers (Hao, et al., 2017).

The manufacturing of Li-ions has shown a continuous growth, and is even expected to grow faster in the near future. The problem, however lies under the maximum production capacity the companies can offer. In manufacturing of electric vehicles, the demand of Li-ions has the potential to reach around 60 GWh in 2020. Considering the estimated global production capacity to be around 43 GWh in 2016, the demand of Li-ions would reach meet this capacity after 2019 (Lebedeva et al., 2016). As for Lithium consumption as a material, the consumption at 2007 accounted for around 5189 tonnes (Ziemann et al., 2012), and the consumption of Lithium ion batteries in 2008 accounted for 20024 tonnes. From that sense, the amount of Lithium in Li-ion batteries is estimated to be the consumption of Lithium as a material divided by the global consumption of Li-ion batteries, leading to 0.26 tonnes of lithium per each tonne of lithium ion batteries. However, there is a high potential for an increase in the Li consumption which is related to the increase of Li-ions demand consequently, the main reason is the emerge of the electric drive vehicles globally. However, it is still hard to quantify this growth, which primarily depends on the growth factors that will be considered (Olivetti et al., 2017).

The collection of end-of-life products containing lithium differs according to the product type (Figure 3.16 – F5). The collection process of end-of-life EV is considerably easier than other products due to the strict EU legislations in the automotive industry, in addition to the shape factor of products. In case of portable Li-ions, the collection end-of-life units is improving continuously but with minor exceptions in some EU countries. The overall collecting rate has reached at least 45% in the year 2016 and is gradually increasing (Arbor, 2016). For other products, including pharmaceutical products, lubricating greases and other uses, lithium is not traced, and thus it is not collected. Therefore, lithium is eventually lost in these particular sectors of Li demanding products.

The recycling stage in the lithium life cycle in EU (Figure 3.16 – F7) is not well established due to the difficulties in separating the lithium from other metals. However, Lithium is being recovered not as an element but with the whole assembled products. In the EV industry,

firstly, and after the collection took place, spent batteries are removed from the vehicles, and they are sent to further processing. the batteries undergo physical separation from which some metals are melted, casted and recovered. Then, parts are reassembled forming a new Li-ion battery that is installed in new EVs, contributing to the reuse of materials including lithium as a major part of the battery (Engel and Macht, 2016), the problem however, is that some metals inside the spent batteries is hard to separate because of complicated structure, including lithium. So although batteries are reused, materials including lithium are actually replaced with virgin material. As for portable Li-ion batteries, recycling is not the common trend, neither in the EU nor in the world wide, because there is no logical reason for recycling batteries from small mobile phones. Instead, these portable batteries are collected and sent to landfills (Zeng and Li, 2014).



**Figure 3.16 Lithium life cycle in EU.** Boxes represent the stocks of material prior to usage. Circle represent stocks of material during the usage. Arrowed boxes represent the stocks of material in post consumption stages. Arrows represent the flow of material. Dashed arrows represent the imports and export of material

### 3.2 Mathematical Formulations

The stock-flow diagrams of materials correspond to a set of mathematical formulations and derivatives. Unlike the rigid structure of material flow at a certain year. The dynamic behavior of the system dynamics model leads to the variation of flow results that are different from one time to another, based mainly on the interdependencies between the variables, and the different parameter that are directly and indirectly affecting the system as a whole, or some parts of the system.

The mathematical representations of the material flow are based on the stock-flow diagram of each material life cycle. At any time  $t$ , the amount of material inside a stock is represented through the integral of the difference between the inflows and the outflows to and from the stock, which corresponds to the following equation:

$$Stock(t) = \int_{t_0}^t (Inflow(t) - Outflow(t))dt + Stock(t_0) \quad (1)$$

The first source of materials comes from extraction activities ( $V_R(t)$ ) or imports of virgin material into the European material life cycle ( $IV_R(t)$ ). Those two flows of virgin material enter the stock of primary material ( $VS(t)$ ) (Figure 3.17). From this stock, represented by this equation:

$$VS(t) = \int_{t_0}^t (V_R(t) + IV_R(t) - VW_R(t) - P_R(t))dt + VS(t_0) \quad (2)$$

Where ( $P_R(t)$ ) is primary material outflows as the processing stage starts to process the primary material into processed material, and ( $VW_R(t)$ ) is the waste associated with the processing of virgin material. another source of processed material comes from the imports activities ( $IP_R(t)$ ), contributing to the total amount of processed material in the EU ( $PS(t)$ ) (Figure 3.17) formulated through this equation:

$$PS(t) = \int_{t_0}^t (P_R(t) + IP_R(t) - PW_R(t) - EP_R(t) - EPW_R(t) - M_R(t))dt + PS(t_0) \quad (3)$$

Where ( $EP_R(t)$ ) is the exports of processed material, and ( $M_R(t)$ ) is the manufacturing rate. Also, and due to processing activities, there is always an amount of waste as a result from these activities, where some of these wastes are exported ( $EPW_R(t)$ ). Others stay in the EU and they are either landfilled or lost in the environment ( $PW_R(t)$ ). This is particularly a special case that depends primarily on each material life cycle. The material in ( $M_R(t)$ ) goes to the complex phase, corresponding to different types of products in the system. Considering

the different types of products each material contributes, the amount of material at each product stock ( $MS(t)$ ) (Figure 3.17) corresponds to the following equation:

$$MS(t) = \int_{t_0}^t (M_R(t) + IM_R(t) + R_R(t) - EM_R(t) - C_R(t))dt + MS(t_0) \quad (4)$$

Where ( $IM_R(t)$ ) and ( $EM_R(t)$ ) are the imports and exports of material from and to the EU respectively, these inflows and outflows represents the amount of pure material inside the products traded. Also, recycled material flow ( $R_R(t)$ ) contributes to the manufactured products, corresponding to the material from secondary sources. On the other hand, ( $C_R(t)$ ) corresponds to the outflow of the material to the next stage, which is the consumption level ( $CS(t)$ ) (Figure 3.17), formulated by the following equation:

$$CS(t) = \int_{t_0}^t (C_R(t) - EOF_R(t) - CL_R(t))dt + CS(t_0) \quad (5)$$

The consumption stage is primarily driven by the demand estimations for each product line. It is where the products are being used until their end-of-life. When the products reach the end-of-life, the ideal next step would be to collect these end-of-life products ( $EOF_R(t)$ ) for further processing in the post consumption stages. For each material, however, the collecting systems and procedures are different and follow different behaviors. For phosphorus for example, the material is not physically transporting between the different life cycle stages. It is being transported through different chemical forms and in different shapes, where phosphorus goes into the consumption stage as grown crops and food, it goes from the end-of-life gate as human excreta and animal manure. Generally, and before the collection takes place, some amount of material is lost and eventually escapes to the environment ( $CL_R(t)$ ). The amount of material in products collected ( $CoS(t)$ ) (Figure 3.17) is represented through this following equation:

$$CoS(t) = \int_{t_0}^t (EOF_R(t) - L_R(t) - R_R(t))dt + CoS(t_0) \quad (6)$$

Where ( $R_R(t)$ ) is the outflow of material recycled. The amount of material heading for the recycling process goes and are found in the recycled material stock, before heading for reuse either for end-users or for processing or manufacturing companies to be then reused later on subsequently. On the other hand, and due to deficiencies in recycling (assuming a non-full efficiency for recycling), landfilling of material does occur ( $L_R(t)$ ) and it goes primarily from the collected materials. These landfilled products correspond to landfilling policies by the EU at which they go to special sites prepared mainly for such purposes.



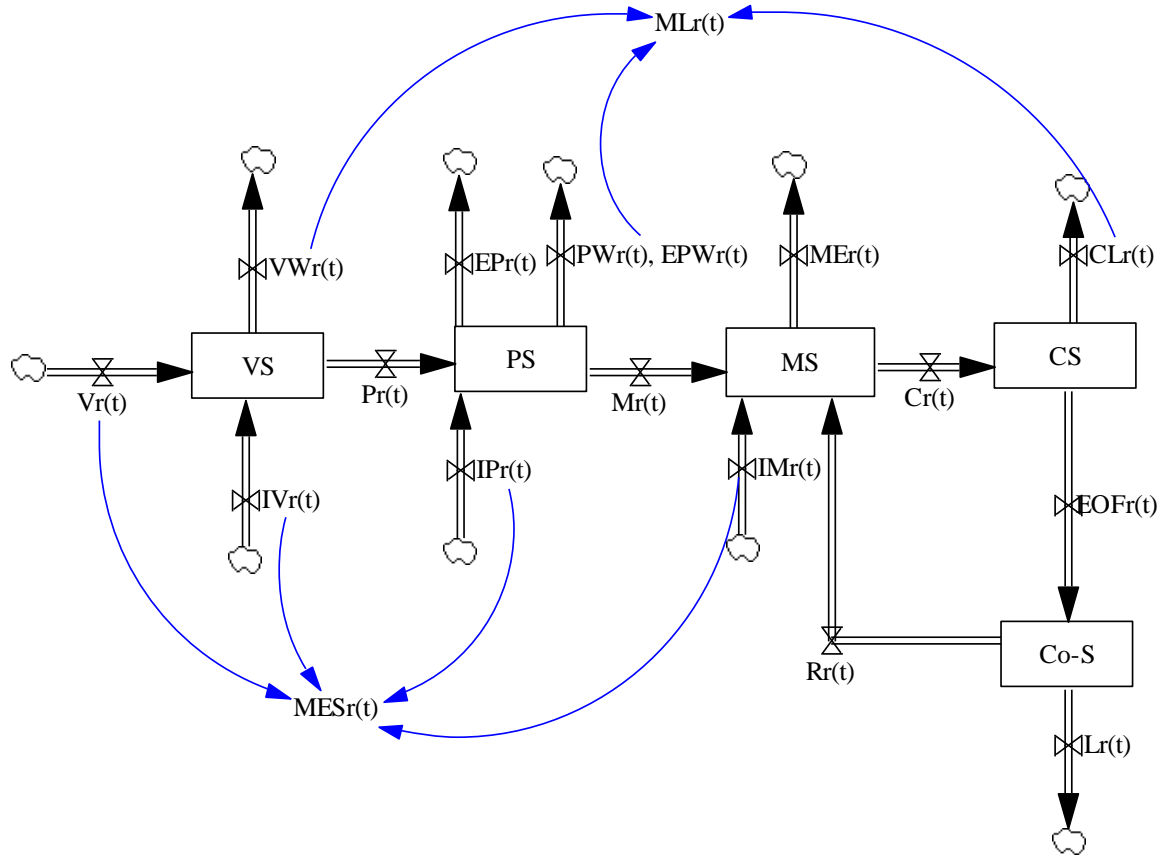
The total amount of material entering the life cycle of material corresponds to the summation of materials entering each life cycle stage independently. This entering behavior of materials is due to the importing activities by the European Union, where the total amount of these material ( $MES_R(t)$ ) (Figure 3.17) can be represented through the following equation:

$$MES_R(t) = V_R(t) + IV_R(t) + IP_R(t) + IM_R(t) \quad (7)$$

On the other hand, the total loss of material corresponds to the wastes generated at different life cycle stages, excluding those collected and either recycled or landfilled. Shortly, at some stages, and due to the mining, processing and manufacturing of products, residues of materials occur and are considered to be loss unless specific treating facilities are responsible for collecting and sending them to further utilization processes. In addition, some materials are lost at the usage stage, contributing to the total loss in the lifecycle. The total amount of material lost ( $ML_R(t)$ ) (Figure 3.17) is thus formulated through this mathematical representation.

$$ML_R(t) = VW_R(t) + PW_R(t) + CL_R(t) \quad (8)$$

The mathematical formulation of the recycled material and landfilled material is simply  $R_R(t)$  and  $L_R(t)$  respectively. In some cases, such as phosphorus, the amount of recycled material originates from different sources, heading to the same sink (fertilizers). In this case, the amount of recycled material is  $\sum_1^n R_R(t)n$  and the amount of landfilled material is  $\sum_1^n L_R(t)n$



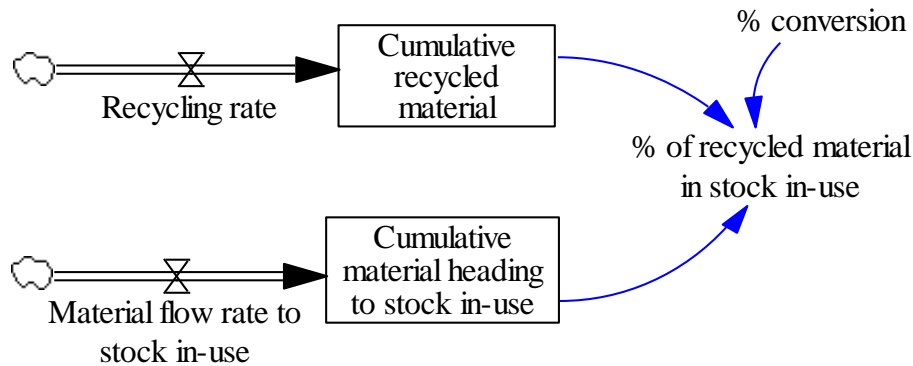
**Figure 3.17 Model development for the main flows and stocks under study.** Boxes corresponds to the stocks. Straight arrows correspond to the flow of material. Blue arrows (arched) correspond to the relationships

The calculation of the percentage of recycled material at time  $t$  in main stock in-use is done through calculating the cumulative amount of recycled material and the cumulative amount of material entering the stock, regardless of sources. Hence, the percentage of recycled material inside the main stock in-use is determine through the following equation:

$$\%RM = \frac{\int_{t_0}^t (R_R(t))dt + R(t_0)}{\int_{t_0}^t (R_R(t) + OM_R(t))dt + MS(t_0)} \times 100 \quad (9)$$

Where  $R(t_0)$  is the amount of cumulative recycled material at time  $t_0$ , and  $OM(t_0)$  is the material flow from other sources (within the life cycle or material from imports), and  $MS(t_0)$  is the cumulative amount of materials in the stock at time  $t_0$ . The modelling part of the percentage of recycled material inside the main stocks in-use depends primarily on the recycled material flow and to the total material flowing into the same stock as can be shown from Eq(). The modelling of these variables in order to achieve the results can be seen in

figure 3.18. Where the annual amount of recycled material flow is leading to the cumulative stock of recycled material, and same as for the total flow of material, which is also contributing to the cumulative stock of material from all sources.

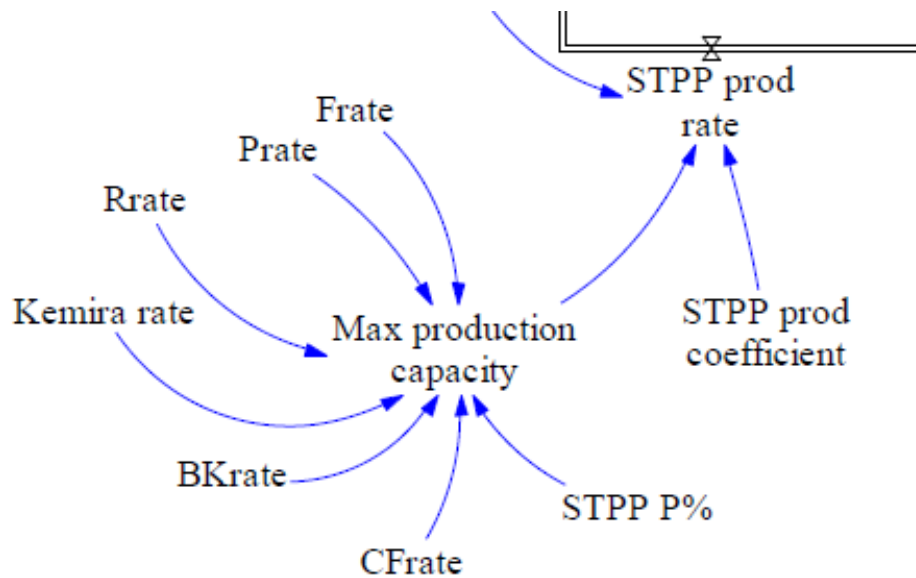


**Figure 3.18 Model development for determining the percentage of recycled material in stock in-use.** Boxes corresponds to the stocks. Straight arrows correspond to the flow of material. Blue arrows (arched) correspond to the relationships

### 3.3 Modelling the flow of materials

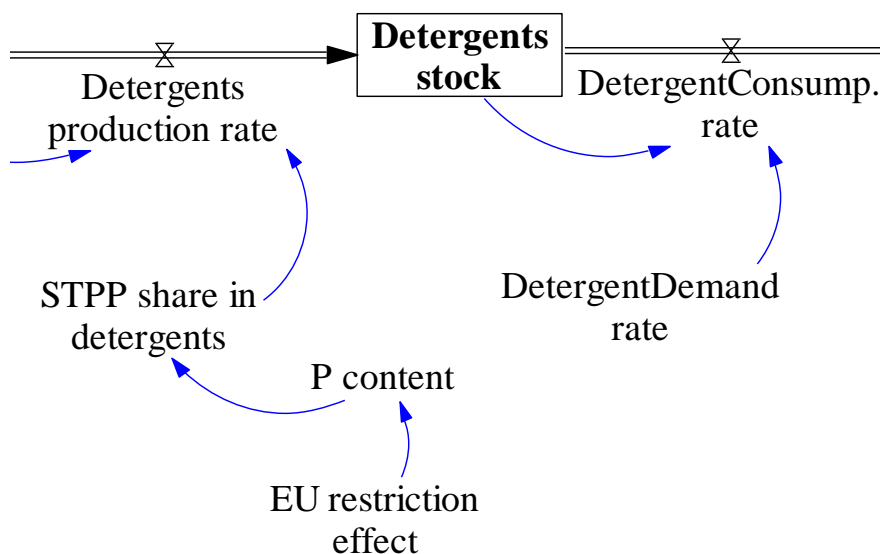
#### 3.3.1 Phosphorus

The system dynamics modeling of phosphorus lifecycle starts from the virgin material entering the primary stock from two inflows. The production stage is modeled through the main outflows from the phosphoric acid stock, contributing to fertilizers, food additives and detergents. For the Detergent production, the production process is modeled based on the fact that the inclusion of phosphorus material by adding STPP is eventually going to an end. Also, and by considering the maximum production of major STPP producers in the EU, the maximum production capacity is considered based on data from Glennie et al (2002) (Figure 3.19).



**Figure 3.19 Model development of STPP production rate.** Blue arrows (arched) correspond to the relationships between variables and parameters.

The use of STPP in the EU is currently limited due to EU policies on restricting the use of STPP in the detergent industry. This fact is important to consider when modelling the P life cycle. To show this effect, the EU restriction effect is added to the system. It affects directly the phosphorus content in detergent builders, and thus affects the STPP content share in detergents production processes.

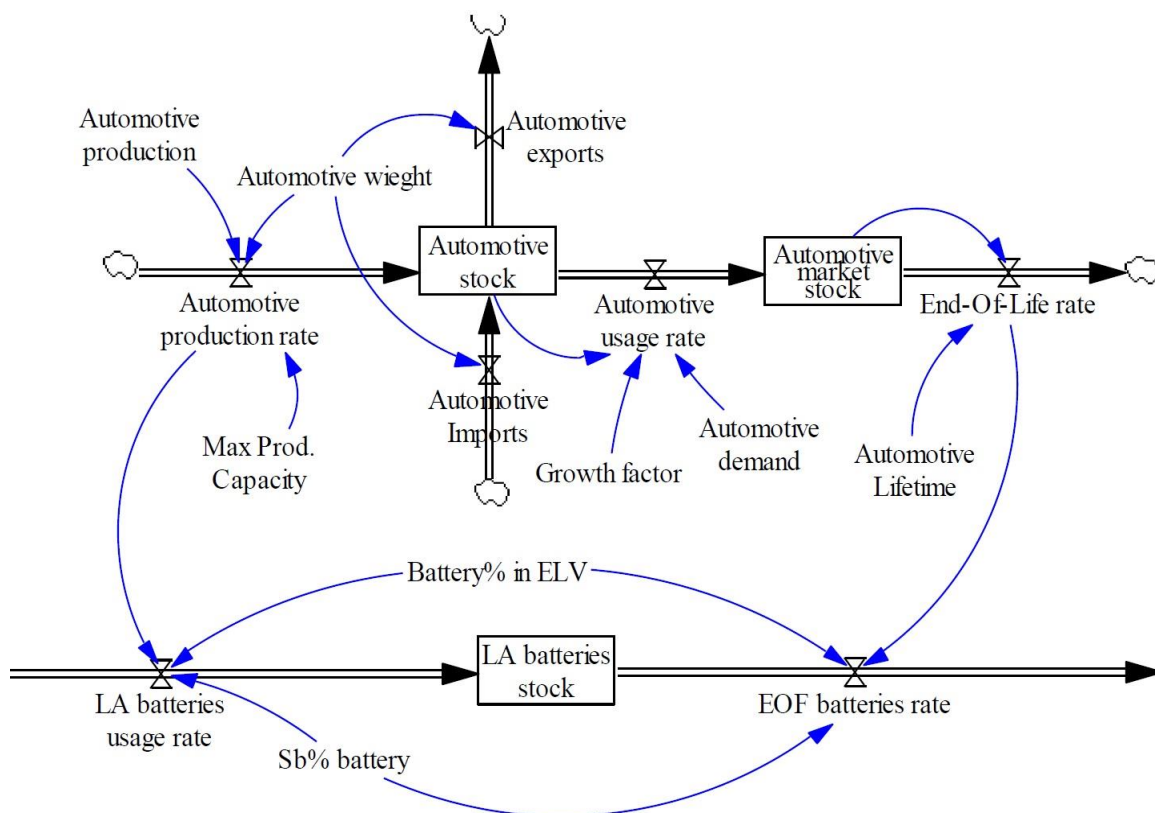


**Figure 3.20 Model development of Detergents production.** Boxes corresponds to the stocks. Straight arrows correspond to the flow of material. Blue arrows (arched) correspond to the relationships between variables and parameters.

### 3.3.2 Antimony

The first stage of the antimony life cycle model starts with the inflow of primary material which is represented by the imports activities. Consequently, the material flows to the subsequent stages. At some stages, the material flow is affected by external parameters, particularly in the usage stage, where the flow depends primarily on other products demand.

In the usage stage, the formulation of the dynamic system is done through including the external parameters that affect the consumption behavior. For the consumption of lead acid batteries, and considering the common use of these batteries in the automotive industry, the dynamic behavior of the usage rate of the lead acid batteries is dependent on the automotive market (Figure 3.21). The usage of lead-acid batteries goes for the production of automotive. As much as automotive are being traded in Europe, consequently lead-acid batteries exist, this existing behavior is represented through the lead-acid batteries stock. The final stage at which the batteries exit the stock is when the automotive reach the end-of-life stage.

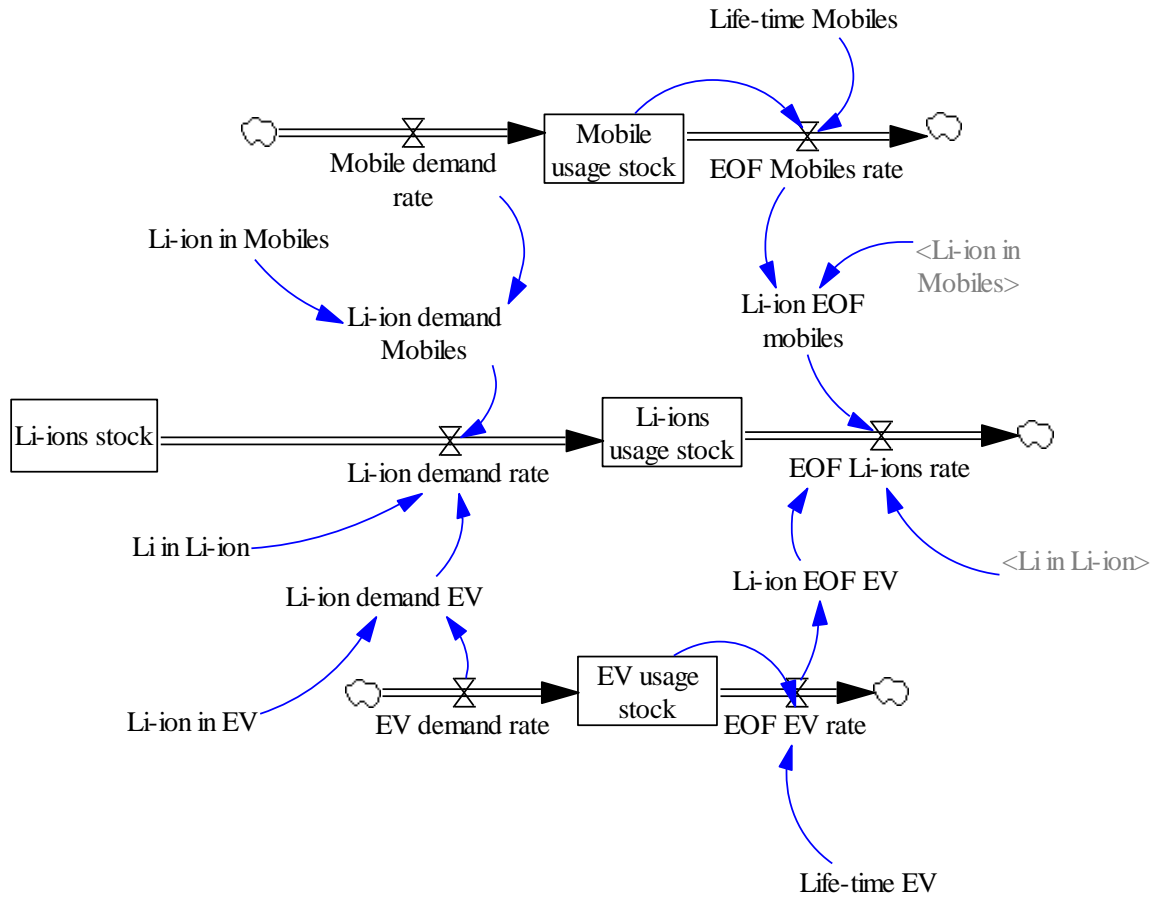


**Figure 3.21 Model development of material flow in Lead-acid batteries.** Boxes corresponds to the stocks. Straight arrows correspond to the flow of material. Blue arrows (arched) correspond to the relationships between variables and parameters.

### 3.3.3 Lithium

The modelling of the flow of lithium in the EU is done considering the available data for each life cycle stage. In this study, the material flow is considered in two products sectors, those are the Li-ion battery and glass sectors. Whereas other sectors such as aluminum smelting, steel casting, pharmaceutical sectors are not considered in this study due to the uncertain fate of lithium flow and thus they are considered as loss.

The flow of lithium in the Li-ion supply chain follows primarily the demand of different products independently, including Mobile phones and newly electric vehicles. The dynamic behavior of the lithium flow in these sectors is modelled as shown in figure 3.22. Modelling the flow of lithium in Li-ions is hard without including the market of EVs and mobile phones as two separate flows. Because each market has its own dynamic behavior and thus, affects the flow of Li-ion batteries differently, for example, the demand rate and the lifetime of products are different. Conservation of units is a primary priority. Hence, the conversion of units into exact Li tonnes is done through introducing the converting variables and applying them to the system.



**Figure 3.22 Model development of material flow in Li-ion batteries.** Boxes corresponds to the stocks. Straight arrows correspond to the flow of material. Blue arrows (arched) correspond to the relationships between variables and parameters.

## 4 RESULTS

In this section, the results are primarily meant to answer the research questions formulated, based on the research objectives. After creating the model via Vensim modelling software, and including all the parameters, variables and relationship between variables, the results are obtained. The simulation period is set to be 100 years (2000-2100). Further, the material flow results are in tonnes. For each material, the flow corresponds to the exact content of material. For phosphorus, the material flow unit is in tonnes P, for antimony, the material flow unit is in tonnes Sb, and for lithium, the material flow unit is in Li.

### 4.1 Phosphorus

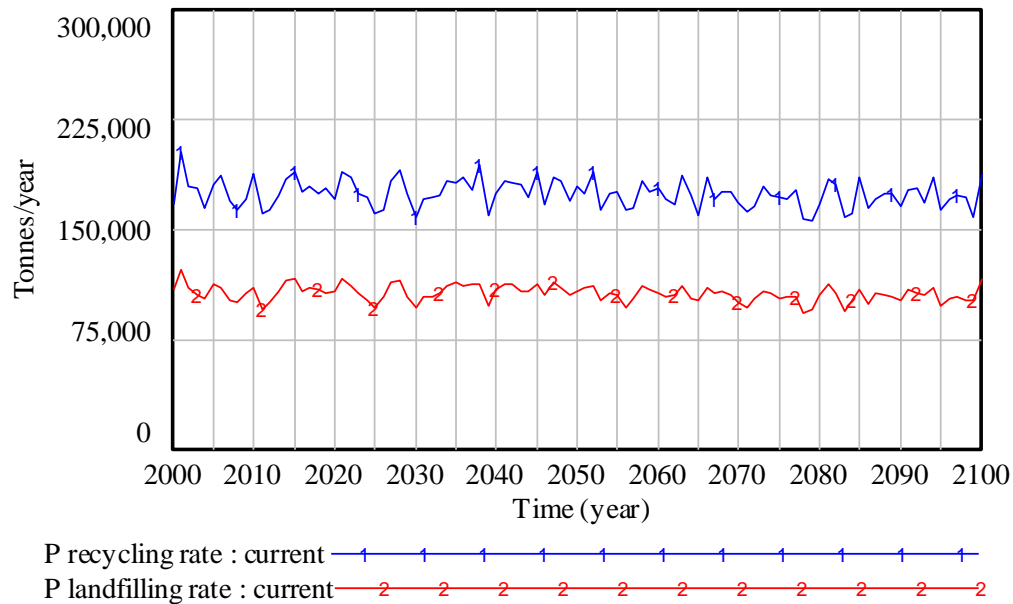
The dynamic representation of the phosphorus life cycle in EU contributes to the quantity estimations of P flow at different stages. Figure 4.1 shows the amount of P entering the system and the amount leaving the system as loss. Based on the estimated results estimations, an average of 2336880 tonnes P enters the life cycle in EU (Table 4.1). This average amount of P corresponds to the extracted amount of primary phosphorus from phosphate rock, and the imports of phosphorus at each stage of the P life cycle including primary, processing and manufacturing stages.

At the other end of the P life cycle, the average amount of material lost is 962490 tonnes P (Table 4.1). This amount corresponds to the amount lost at different stages as well, including the mining, beneficiation, processing, agriculture run off, industrial loss, and material loss from waste management operations. Considering this amount of lost material, the EU P life cycle efficiently relies on the rest amount of P. This amount of material loss corresponds to the amount lost during different life cycle stages. Some of these amounts are lost during mining of primary material and the processing operations into phosphoric acid. Others are lost in the food supply chains due to the human consumption behavior. In post consumption stages, material is lost due to wastewater treating facilities, where lost P goes to the water bodies, lakes and inner waters. However, most of these amount loss is due to the agricultural erosions from fertilizers applied to the soil.





would exceed the landfilling capacity in the EU, the dynamic behavior of the landfilling rate would follow a certain different trend. Despite the fluctuating behavior of the trends of both flows (landfilling and recycling), there is a slight decreasing trend overall the simulation period (2000-2100). The reason behind this slight decrease is the gradual restriction on the use of phosphate additives to the detergent industry in EU and particularly the STPP.



**Figure 4.2 Simulation results for P recycled and P landfilled.** Blue line with mark (1) corresponds to the amount of P recycled. Red line with mark (2) corresponds to the amount of P landfilled.

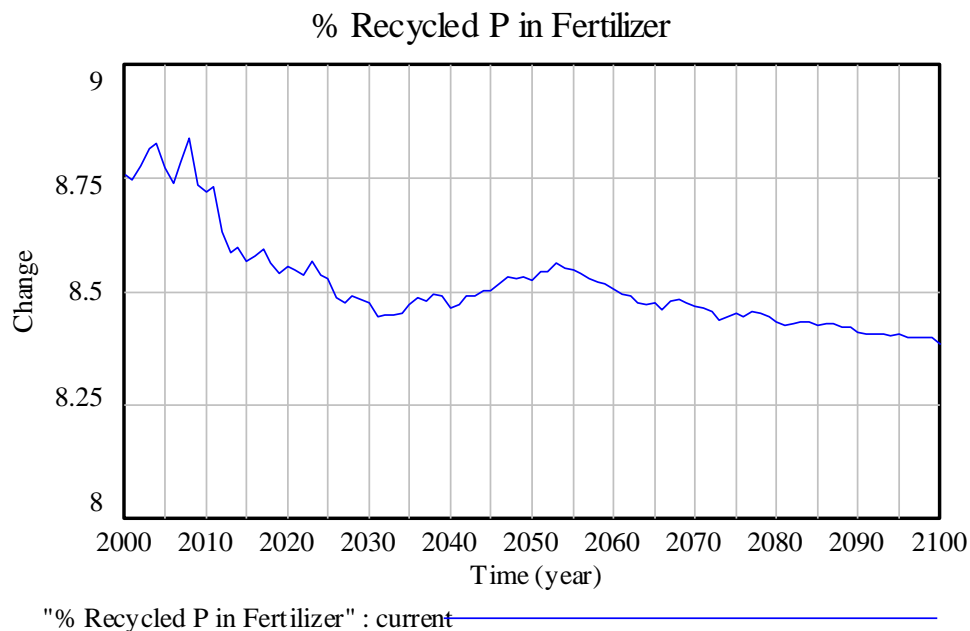
**Table 4.1 Summary of results of material flow in phosphorus life cycle in EU.** All numbers corresponds to the average amounts during the simulation period (2000-2100). Units are in Tonnes P.

Material entering the system	Material loss	Material recycled	Material landfilled
2336880	962490	174694	106616

In the case of phosphorus, the output of recycling processes in all waste streams is meant to be for agriculture applications, or phosphate fertilizers. Figure 4.3 shows the percentage estimations of the amount of recycled material to the total amount in fertilizers. As an

average, around 8.6% of P in fertilizers originates from recycling (Table 4.2). Further, the graphical representation of the results shows a general decreasing trend with minor fluctuations throughout the duration from 2000 to 2100.

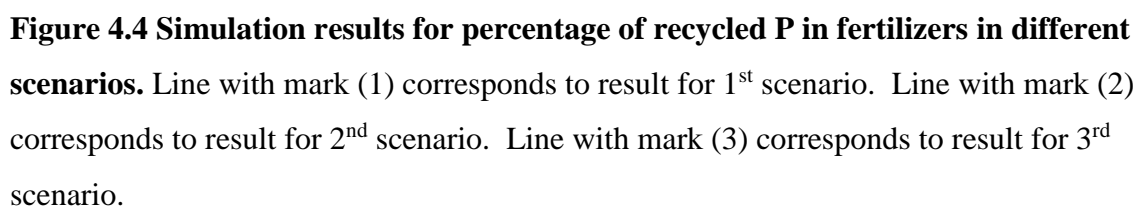
The change of the percentage of recycled material in fertilizers depend on the flow of materials from recycling and from other activities. The decreasing trend of this percentage in figure 4.3 is due to the gradual decrease of recycling rate with the passage of time. On the other side, the amount of material from other sources (Imports and production of fertilizers) is on an increasing trend due to the dependency of EU on the imports to a high level. These two factors contribute to a decreasing trend in the percentage of recycled P in fertilizers. The reason for the decreasing trend of P recycling is the decrease of P in wastewater. In the detergent industry, and specifically in the production of Sodium triphosphates (STPP), the EU has introduced new policies to restrict or to limit the use of phosphates in detergent builders, in order to avoid the potential damage to lakes and waterbodies and to protect them from eutrophication.



**Figure 4.3 Simulation results for percentage of recycled P in fertilizers**

The scenarios applied to the P life cycle corresponds to the improvements on recycling efficiencies of different waste streams. Improving the recycling is done separately for each waste stream, those are the wastewater stream and the solid waste stream. at which 15% is added to the recycling efficiencies in both streams equally in each scenario.

- The change in the percentage of the recycled phosphorus in fertilizers can be seen after applying the three different scenarios to the system (Figure 4.4). The dynamic behaviors of the percentages follow the same trend; this is due to the fact the recycling improvement is assumed to be stable during the duration of the simulation. The average percentage of recycled P in fertilizers is 11.08% in 1<sup>st</sup> scenario, 13.42% in 2<sup>nd</sup> scenario and 15.63% in 3<sup>rd</sup> scenario (Table 4.2).



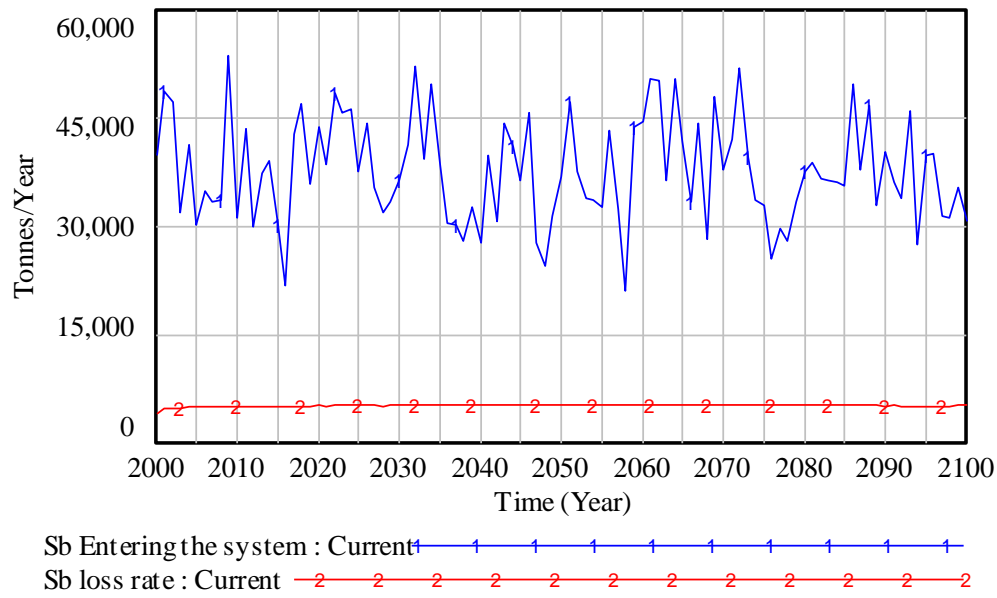
**Table 4.2 Summary results of the percentage of recycled phosphorus in fertilizers.** All numbers correspond to the average estimation during the simulation period (2000-2100). Unit is Percent (%)

<b>Current</b>	<b>1<sup>st</sup> Scenario</b>	<b>2<sup>nd</sup> Scenario</b>	<b>3<sup>rd</sup> scenario</b>
8.6	11.08	13.42	15.63

## 4.2 Antimony

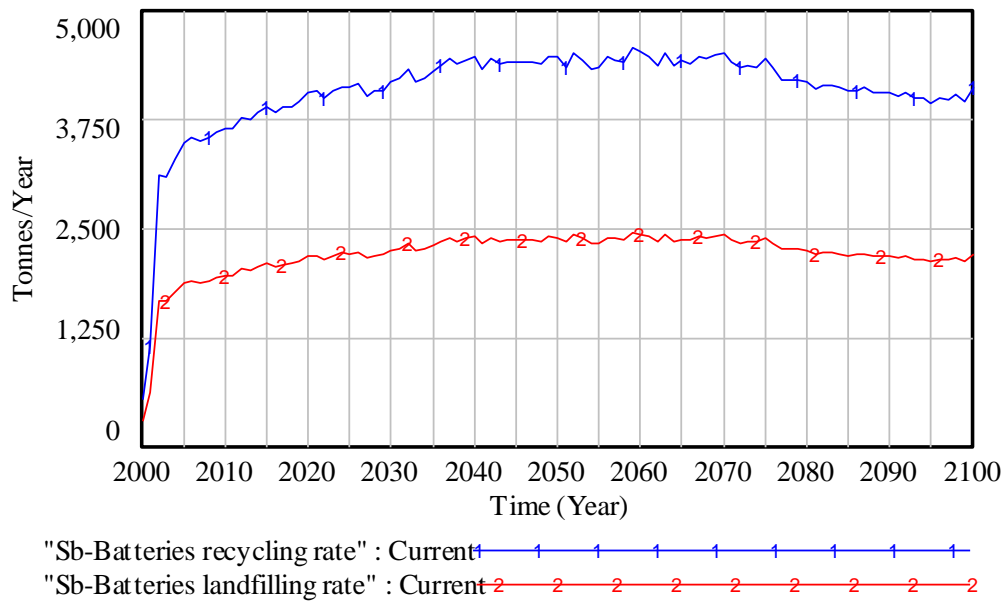
The simulation results for the Sb life cycle corresponds to the amount estimations for material flow in two sectors, lead-acid batteries sector and other uses sector. The other uses sector corresponds to the use of Sb in textiles, PET applications and electronics. For both sectors, results are shown separately.

The primary results of Sb flow are shown in figure 4.5. This figure corresponds to the amount of Sb entering the system, and the amount leaving the system as loss. The results of the Sb flow into the system reflects the local mining of Sb concentrates and the imports of Sb in different life cycle stages. The average amount of Sb entering the system is 37310 tonnes Sb. This amount corresponds to the imports of Sb in different forms to different life cycle stages, including processing (as Sb ores) and manufacturing stages (as processed Sb metal for further manufacturing), in addition to finished and semi-finished products (in the form of Sb oxides, alloys, batteries textiles, PET and electronics). Throughout the Sb life cycle in EU, the average material lost is 5130 tonnes Sb. The amount of material lost is a result of uncollected end of life products, in addition to waste residues from processing operations of Sb metal.



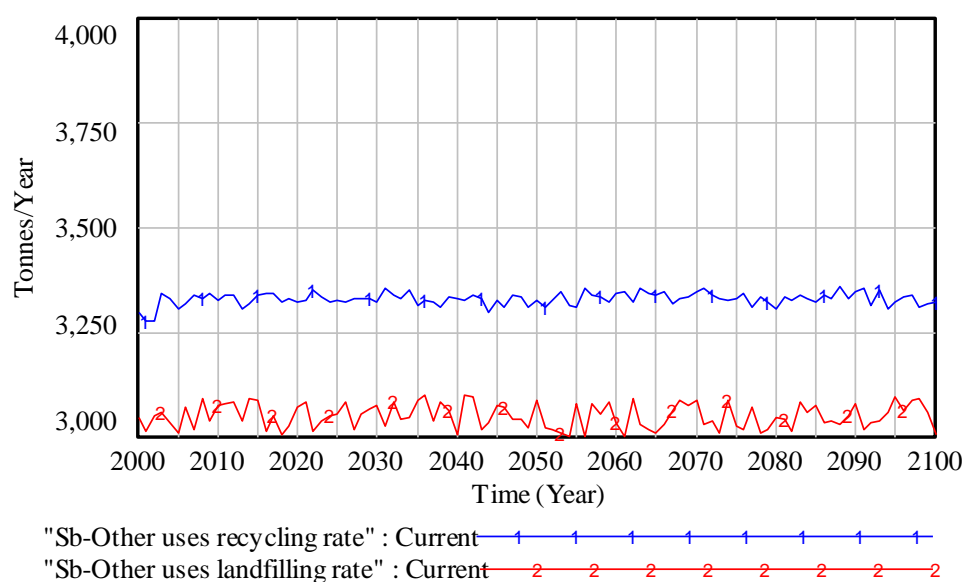
**Figure 4.5 Simulation results for Sb entering the system and Sb loss.** Blue line with mark (1) corresponds to the amount of Sb entering the system. Red line with mark (2) corresponds to the amount of Sb loss.

In the sector of batteries manufacturing, the flow of Sb depends heavily on the automotive industry, assuming that all the production of lead acid batteries is dedicated for the automotive industry in the European Union. In this sub model, the change in the market of the automotive industry is important to consider in order to estimate the Sb flows in that sector. Figure 4.6 shows the dynamic behavior of the recycled material flow from end-of life lead-acid batteries. The average amount of material recycled is 3760 tonnes. The trend behavior of the recycled material flow into the lead acid batteries stock follows the trend of the automotive industry in EU, and the EOF vehicles are the main indicator of the dynamic behavior of the flow of lead acid batteries. Further, the landfilling rate follows the same trend as well, keeping in mind that this flow, like the recycled material flow, follows the trend of EOF vehicles that are collected, but not recycled. The results show estimates the average amount of material landfilled to be



**Figure 4.6 Simulation results for Sb recycled and Sb landfilled from spent lead-acid batteries.** Blue line with mark (1) corresponds to the amount of Sb recycled. Red line with mark (2) corresponds to the amount of Sb landfilled

The recycling rates of Sb in the other phases of Sb life cycle can be seen in figure 4.7. The average amount of recycled Sb is 3321 tonnes Sb. The trend of material recycled flow is stable despite the fluctuations. This amount of recycled material corresponds to the recycling of textiles, PET containers and electronic equipment. Considering the same form of material used in each of the products sectors, the total amount of recycled material was considered. The amount of recycled material exceeds the amount of material landfilled or sent to landfilling sites by an average of 3050 tonnes Sb. this amount of landfilled material comes after the waste has been collected, treated but not recycled.



**Figure 4.7 Simulation results for Sb recycled and Sb landfilled from other uses.** Blue line with mark (1) corresponds to the amount of Sb recycled. Red line with mark (2) corresponds to the amount of Sb landfilled

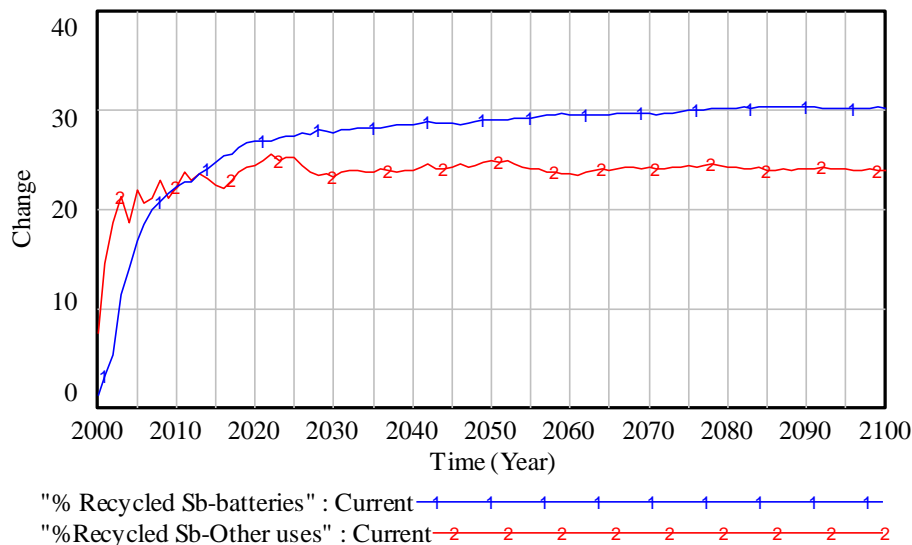
**Table 4.3 Summary of results of material flow in antimony life cycle in EU.** All numbers corresponds to the average amounts during the simulation period (2000-2100). Units are in Tonnes Sb.

	Material recycled	Material landfilled	Material entering the system	Material loss
<b>Sb in Lead-acid Batteries</b>	3760	2024	37310	5130
<b>Sb in Other uses</b>	3321	3050		

The contribution recycled Sb to the lead acid batteries can be seen in figure 4.8. The graphical representation of the change of recycled Sb in the lead-acid batteries shows that around 27% of the total Sb in lead-acid batteries comes from recycling (Table 4.4). The behavior of the trend line experiences a continuous increase until the year 2020 before it stabilizes with a slight increase. The reason behind this increase is the growing efficiency in collecting EOF vehicles due to the introduction of EU directives and legislations on spent vehicles and automobiles. On the other phase of Sb life cycle, the average percentage of



recycled Sb in other uses is 23.3%. The trend line follows the stability form in an early stage. The reason behind this is that the average rates of recycling from one hand, and the average rates of material heading to the other uses stocks are prominently stable.

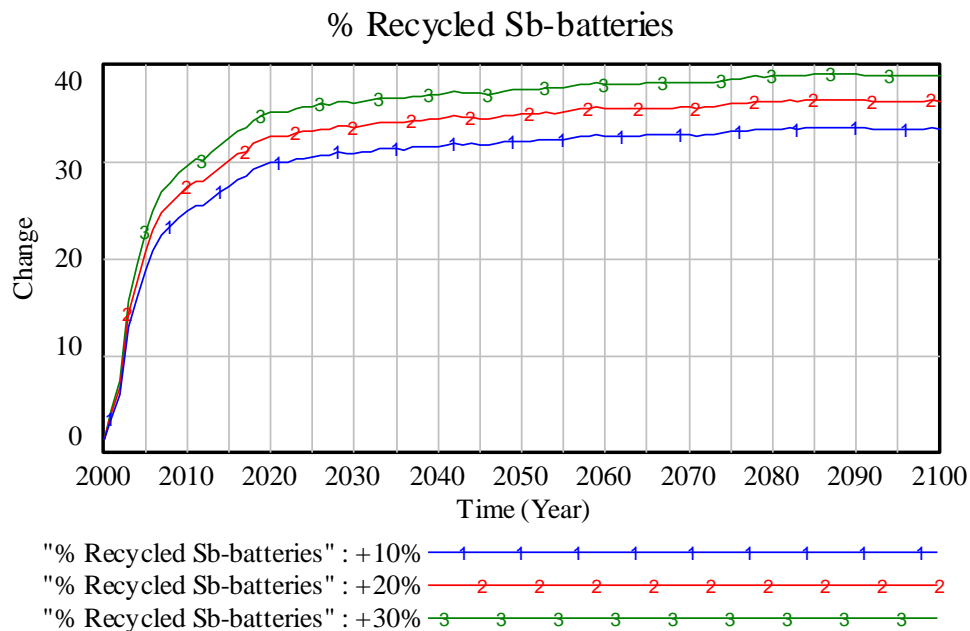


**Figure 4.8 Simulation results for percentage of recycled Sb in Lead-acid batteries and in Other uses.** Blue line with mark (1) corresponds to the change of percentage of recycled Sb in lead-acid batteries. Red line with mark (2) corresponds to the change of percentage of recycled Sb in other uses.

The scenarios applied to investigate the potential change in recycled material in the Sb life cycle corresponds to the improvement of 10% in recycling efficiencies after each iteration. With three scenarios, the improvements done are +10%, +20% and +30%. Considering currently that recycled Sb from lead-acid batteries are around 65% of total lead acid batteries collected for waste management process, these improvements are done accordingly, so that the recycling percentages for material does not exceed the full efficiency (100%). Improving recycling is also done to the textile recycling, PET containers recycling and electronics recycling independently by the same proportions for each scenario.

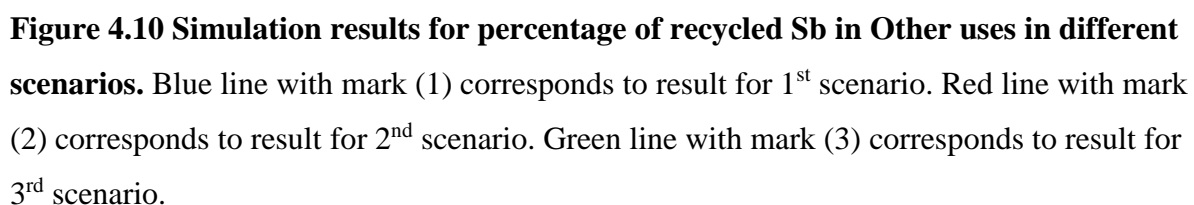
- 1<sup>st</sup> Scenario: 15% added to the recycling efficiencies
- 2<sup>nd</sup> Scenario: 30% added to the recycling efficiencies
- 3<sup>rd</sup> Scenario: 45% added to the recycling efficiencies

Figure 4.9 shows the level of increase of recycled Sb in lead-acid batteries. The lines corresponding to the recycling improvements follow the same trends but with different ranges. The estimates of the average percentage of recycled Sb in lead-acid batteries after recycling improvement becomes 30.23%, 33.24% and 36.14% in the 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> scenario respectively (Table 4.4).



**Figure 4.9 Simulation results for percentage of recycled Sb in Lead-acid batteries in different scenarios.** Blue line with mark (1) corresponds to result for 1<sup>st</sup> scenario. Red line with mark (2) corresponds to result for 2<sup>nd</sup> scenario. Green line with mark (3) corresponds to result for 3<sup>rd</sup> scenario.

In another phase of the Sb life cycle, the increase of recycled Sb in other uses is shown in figure 4.10. Following the same trend in the current situation, the percentage of recycled Sb in other uses increases to 26.55% in the 1<sup>st</sup> scenario, 29.54% in the 2<sup>nd</sup> scenario and 32.3% in the 3<sup>rd</sup> scenario (Table 4.4).

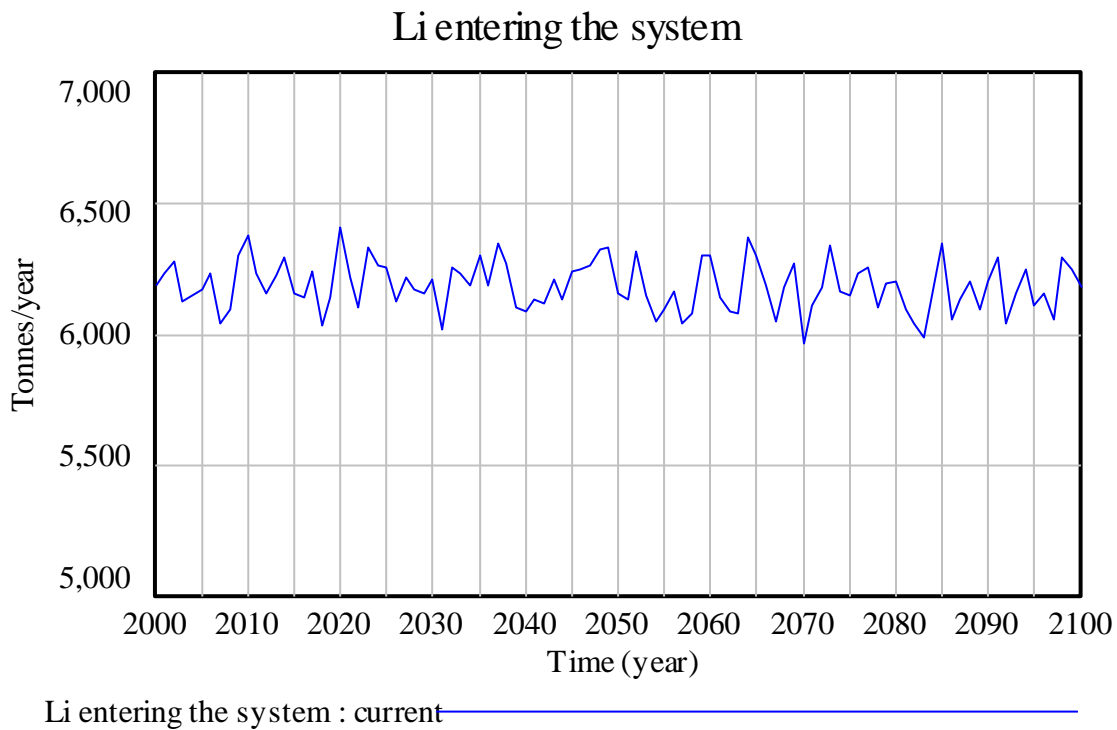


	Current	1 <sup>st</sup> Scenario	2 <sup>nd</sup> Scenario	3 <sup>rd</sup> scenario
<b>Sb in Lead-acid batteries</b>	27	30.23	33.24	36.14
<b>Sb in Other uses</b>	23.3	26.55	29.54	32.3

The results for the Li life cycle in EU corresponds to the amount estimations of material flow in the Li-ion batteries sector.

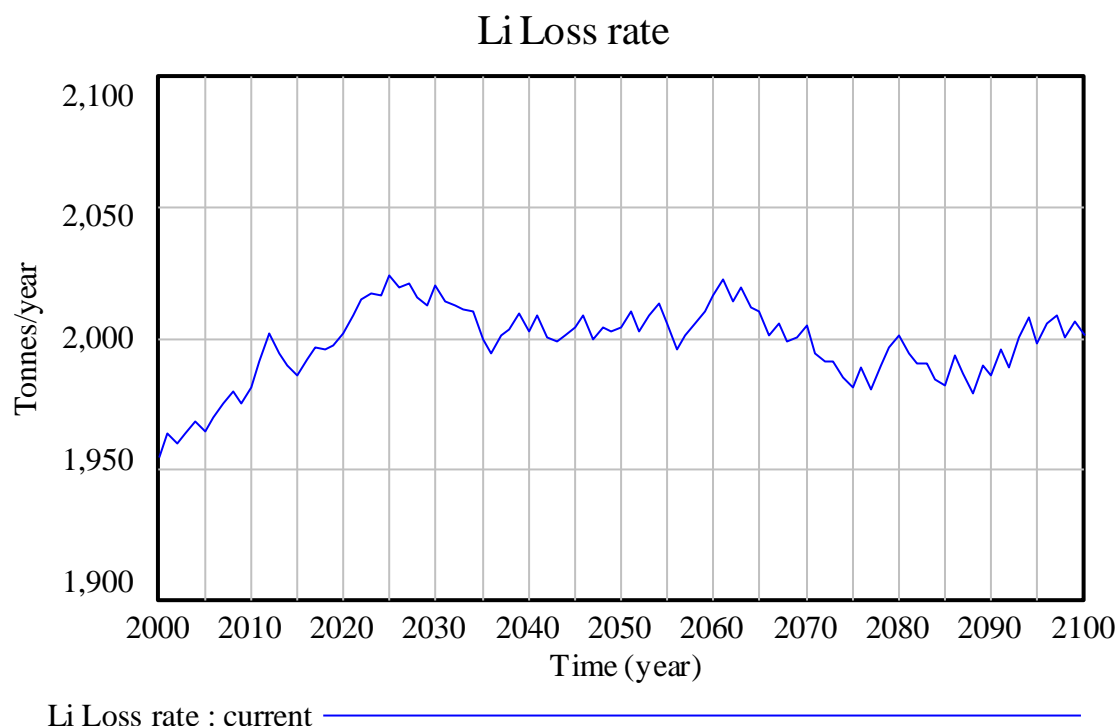
56

materials imported at the different life cycle stages and in different forms, including primary material, processed material and manufactured products. The trend of the material entering the system is considerably stable despite the fluctuations occurring throughout the simulation period (2000-2100). This trend reflects the stability in the EU trading activities and in the mining of material.



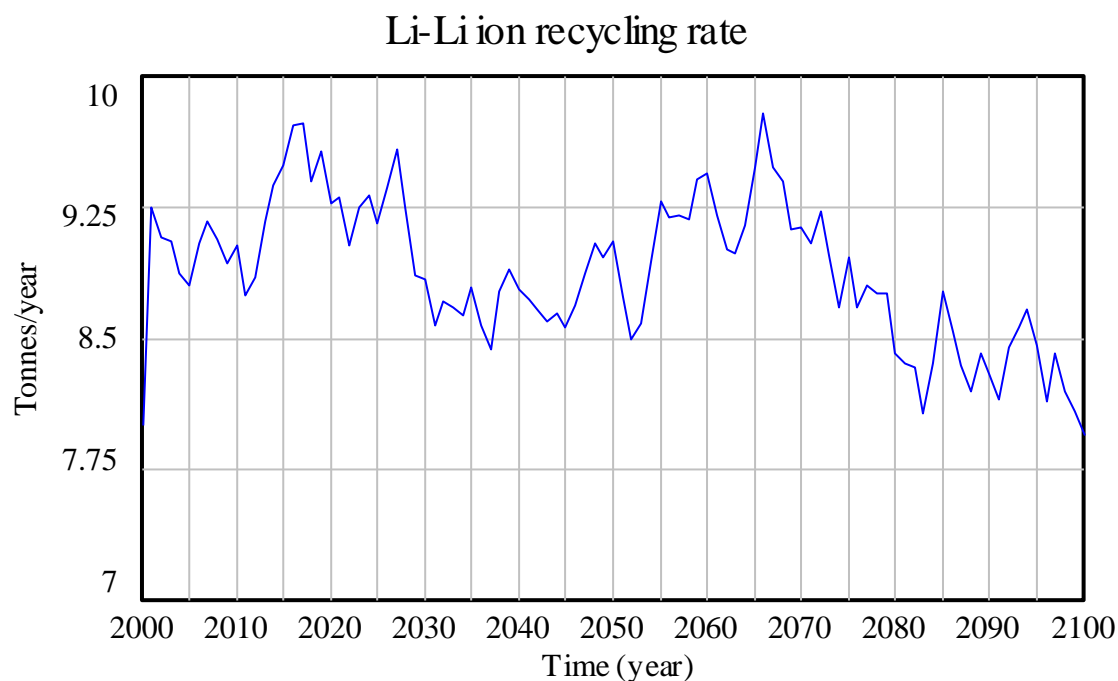
**Figure 4.11 Simulation results for amount of Li entering the system**

On the other hand, the amount of material lost is shown in figure 4.12. The results estimated the annual amount loss to be 1998 tonnes Li as an average (Table 4.5). The trend of material loss experiences a gradual increase until the year 2025, which is the peak, from which it starts fluctuating in a similar behavior. the loss of material in the industries other than the Li-ion batteries is stable. The reason behind this increase is thus the material flow in the Li-ion chain. The flow of material loss in this sector particularly follows the consumption behavior in the first place, and thus. Considering the high life span of Li-ions especially the portable ones, the disposal of spent batteries by consumers to unknown sites increases gradually as the product reaches its end of life stage. Hence, the increase of material loss can be understood.



**Figure 4.12 Simulation results for amount of Li loss**

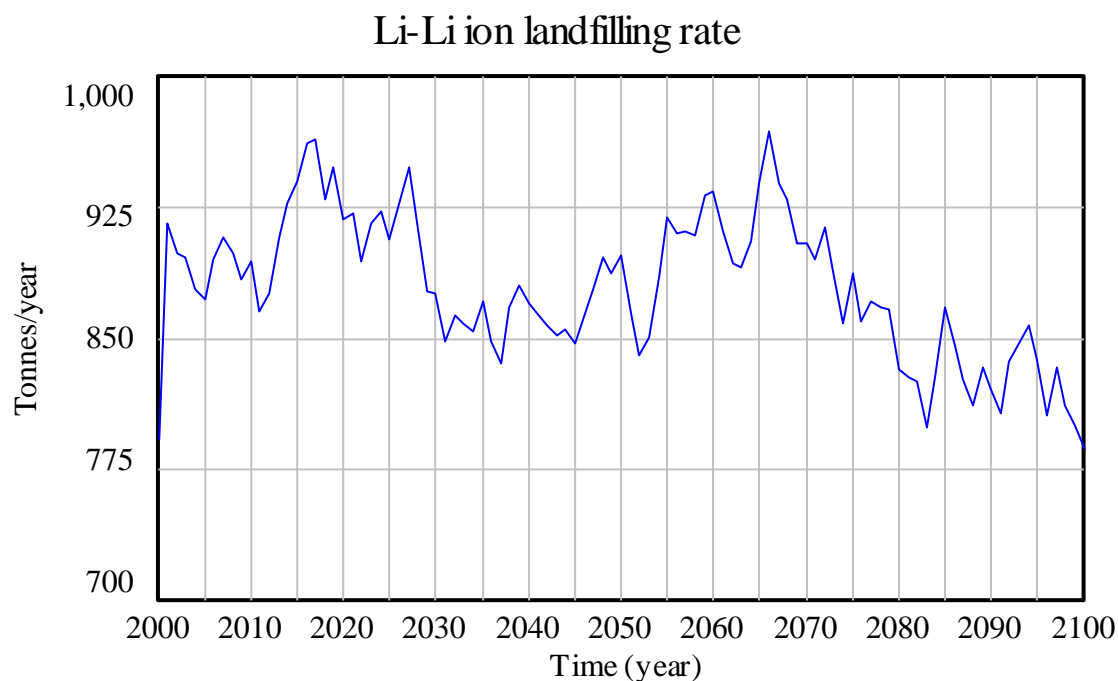
Figure 4.13 shows the amount of Li recycled from the sector of Li-ion batteries. These results correspond to the amount recycled from EVs and mobile phones. The average amount recycled is 8.87 tonnes Li. The trend of the material recycled oscillates to a high level, where it reaches the peak at the year 2066 with an estimated amount of recycling equals 9.78 tonnes Li (Table 4.5). The overall decrease in the trend of recycling can be understood as a result of the long life spans of products being used by consumers. However, some partial increases in the flow of recycled material occurs particularly in the duration (2011-2017) and (2052-2066). The growth of the EV market in the EU contributes to the growth in the use of Li-ions, and consequently increases the amount of lithium in post consumption stages, leading to a higher amount of recycling at some years.



"Li-Li ion recycling rate" : current

**Figure 4.13 Simulation results for amount of Li recycled from spent Li-ion batteries**

Besides recycling, the landfilling rate of Li from the same sector (Li-ions) is shown in figure 4.14, with an average of 880 tonnes Li. The maximum amount of Li landfilled is estimated to be 971 tonnes Li (Table 4.5). The trend of landfilling is identical to that of recycling. The reason behind this is that both flows follow the trend of collected material, prior to the separation point where some amount goes for recycling and the rest goes for landfilling.



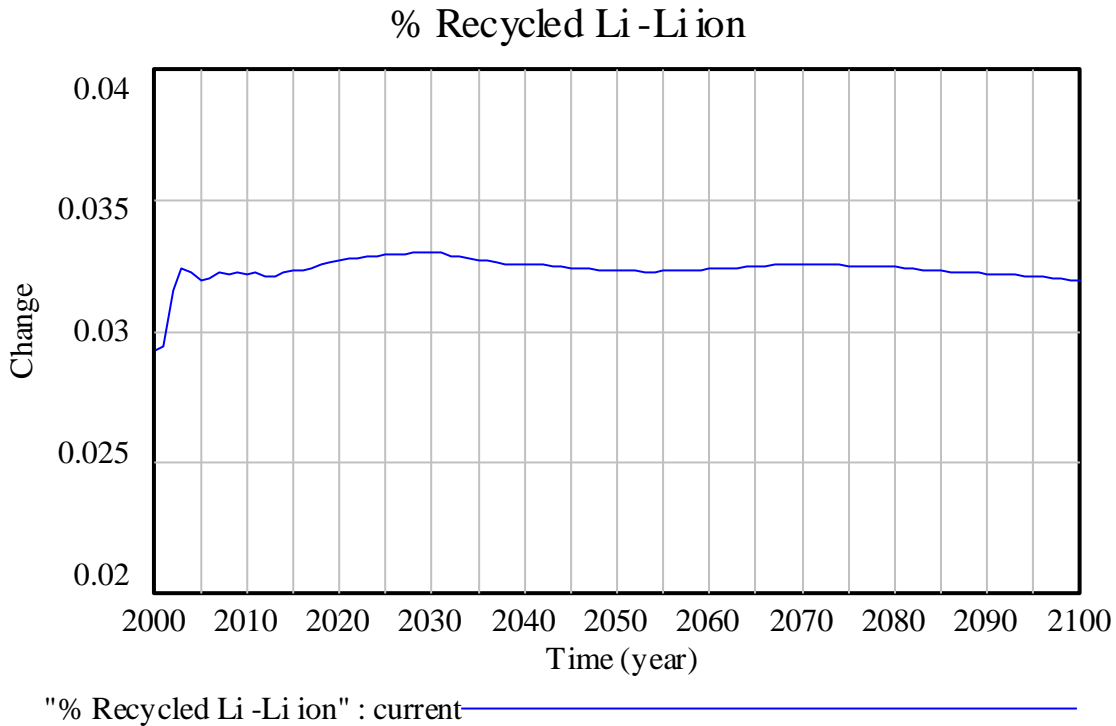
"Li-Li ion landfilling rate" : current

**Figure 4.14 Simulation results for amount of Li landfilled from spent Li-ion batteries**

**Table 4.5 Summary of results of material flow in lithium life cycle in EU.** All numbers corresponds to the average amounts during the simulation period (2000-2100).

<b>Material entering the system</b>	<b>Material loss</b>	<b>Material recycled from Li-ions</b>	<b>Material landfilled from EOF Li-ions</b>
6189	1998	8.87	880

The flow of recycled material to the Li-ion sector contributes to the estimations of the level of recycled Li in this sector at a certain time. The flow of recycled material goes directly to the stock of Li-ions. Figure 4.15 shows the change in the percentage of recycled Li in the stock of Li-ions, leading to an average of 0.0324% (Table 4.6). The estimated results show an overall decrease in the percentage of recycled Li in Li-ions, despite the sharp increase from 2000 to 2003. The preliminary impression about this percentage is that the amount of recycled material in Li-ions is considerably low, leading to around 99.96% of the material to be originating from other sources (imports or mining). This result reflects the inefficiency at some stages of the Li life cycle after the manufacturing processes.



**Figure 4.15 Simulation results for percentage of recycled Li in Li-ion batteries**

The scenarios applied to the Li life cycle corresponds to the improvement on recycling the Li-ion batteries sector specifically. In the three scenarios applied, the improvement on recycling is done through adding 15%, 30% and 45% to the recycling efficiencies of spent Li-ions in each of the three scenario.

- 1<sup>st</sup> Scenario: 15% added to the recycling efficiencies
- 2<sup>nd</sup> Scenario: 30% added to the recycling efficiencies
- 3<sup>rd</sup> Scenario: 45% added to the recycling efficiencies

The estimations of the percentages of recycled Li in Li-ions are shown in figure 4.16. The three lines follow the same trend throughout the simulation duration (2000-2100). The results estimate a considerable change in the level of recycled Li in Li-ions. Starting from an average of 0.0324% in the current situation, the average percentage of recycled material in the Li-ion stock reaches 9.54% in the 1<sup>st</sup> scenario, 17.06% in the 2<sup>nd</sup> scenario and 23.16% in the 3<sup>rd</sup> scenario (Table 4.6). The range of variation in the results is considerably high, which implies the level of significance of Li recycling in the sector of Li-ions particularly.





## **5 DISCUSSION**

### **5.1 Phosphorus**

The results of the phosphorus flow in EU brings up significant implications regarding the actual efficiency of P management in Europe. Where around 2336880 tonnes P enters the system annually, around 962490 tonnes P is lost, contributing to around 41% of material entering the P life cycle in EU. This inefficiency in the P life cycle has been addressed previously implying the high imbalance in the supply chain of phosphorus not only in Europe but globally. This imbalance, if continues, might affect the accessibility to phosphorus which is obtained primarily from the finite source phosphate rock (Withers et al., 2015). Besides the imbalance in the P lifecycle, there are also potential environmental burdens from this amount loss, because the eventual sink of P loss is to the water bodies, which causes eutrophication and damages the water quality if found in excess (Nesme and Withers, 2016).

Among the major losses of phosphorus throughout its life cycle occurs from runoff, due to the agricultural erosion and weathering, and also, they occur from food wastes generated which are not collected (Childers et al., 2011; Scholz and Wellmer, 2015; Chen and Graedel, 2016). The food and agriculture organization of the United Nations has reported the amount of food loss to be around 30% of the total food generated for consumers in the year 2010 (FAO, 2011). In the EU, it was reported by the EU commission that food is lost through the entire supply chain, starting from the agricultural production ending up with household consumption (European Parliament, 2017). This loss of material affects negatively the life cycle of P. The major use of phosphorus is in fertilizers that are primarily used in agricultural production. Hence, uncollected waste from agricultural activities and consequently from consumption activities affects directly the phosphorus life cycle.

### **5.2 Antimony**

The results of the Antimony flow in the European Union reflects the management behavior of the European communities towards Antimony and related products, particularly the lead acid batteries. On the other hand, the material flow follows different parameters and external variables at each life cycle stage independently. Considering the total dependence of the EU on Sb imports, pre consumption life cycle stages are shaped based on the importing policies of the EU, as well as the exports at some stages including the complex phase of

manufacturing, where the lead-acid batteries sector contributes to a significant amount of exports annually with around 70 million units per year.

The percentage of recycled Sb in the stock of lead-acid batteries is affected by different parameters. The first one is the recycling rate of Sb in the end-of-life batteries, the second parameter is the flow of Sb in lead-acid batteries from and to the EU, and the third parameter affects indirectly the recycled Sb flow into the stock of batteries, which is the flow of vehicles from and to the EU. In addition, the flow of recycled Sb reflects the recycling activities done for the automobiles in the EU, where batteries are disassembled and recycled independently. With a current recycling rate of Sb in lead-acid batteries, which is 65% of the total EOF batteries collected, an average of 27% of material inside the batteries stock originates from recycling. Ideally, with all end-of-life products being collected and recycled at this recycling rate, the amount of recycled Sb in the batteries stock would contribute to 39% of the total material. However, and due to loss of material in post consumption and prior to the recycling processes, this percentage decreases.

On the other hand, and with the improvements on the recycling efficiencies for end-of-life lead-acid batteries, the increase of recycled Sb in the stock of lead-acid batteries goes up by 2.04% following the increase of 10% on recycling rates consequently. These results reflect the significance of material loss prior to the recycling processes. If the loss of material at these critical stages is limited and eventually eliminated from the life cycle of Sb in EU, and particularly in the lead-acid batteries sector, there is a potential to increase the recycled material following the improvement on recycling efficiencies resulting in a full efficiency increase. From another perspective, loss of material should also be limited to avoid hazardous effects on the environment. The high contamination level within different metals inside spent batteries lead to serious health effect if discharged (Tian et al., 2017). Even though the results show an increase of recycled material in the batteries stock by 2.04% in each scenario, the recycling processes and their environmental impact should be taken into consideration as well. The recycling of lead-acid batteries contributes to material contaminations as a result of continuous smelting processes and manual recovery (Ericson et al., 2018).

This complex phase includes the different products of PET containers, PVC, Textiles and electronics, where the primary role of Sb in these products serve as a flame retardant. For each product sector, loss of material occurs prior to the recycling stages, which contributes to the lower increase of recycled Sb in the flame retardant stock compared with the higher

increase in recycling rates. The deficiencies in waste management for some product sectors affect directly the recycling activities. In the textile industry, where Sb is used as a flame retardant, statistics show around 19% of post-consumer textiles in the UK are neither recycled nor landfilled (Yasin et al., 2018), meaning that these material are eventually lost. Moreover, the loss of end-of-life products should be urgently discussed, not only because of potential physical shortage of material in the future, but also because of the environmental impact that Antimony has on the environment and the public health if left untreated (Chowdhury et al., 2017).

The overall results of the Sb life cycle in EU goes side by side with the actual situation in the EU, particularly for the amount of recycled Sb in the stocks of manufactured products, where in Netherlands, around 28.8% of total Sb in the market originates from recycling (Gutknecht et al., 2017).

### **5.3 Lithium**

The results of the Lithium life cycle in EU shows around 1998 tonnes Li of material loss. A major contributor to this loss is the pharmaceutical industry, in addition to the other uses of lithium in lubricating greases and other industrial applications. Besides that, it is obvious that the recycled amount of material is considerably low compared with the material entering the system. There are quite various reasons for this result. Firstly, the material loss is an important factor for decreasing the material reaching the treatment stages, and thus to the subsequent stages including recycling. Secondly, the life-span of products requiring Li is significantly high, including the different types of Li-ion batteries used not only for the EVs but also for the mobile phones and energy storage systems. Thirdly, the recycling itself, which is considered to be hard, and sometimes impossible to recover Li from spent batteries (i.e. Li-ions) (Georgi-Maschler et al., 2012). These three factors are the major elements that lead to the results for Li material flow, and particularly the recycled material.

In the Li-ion batteries sector, the high difference of results in each of the scenarios can be understood based on the fact that there is no serious problem in the Li life cycle in Li-ion batteries prior to the recycling and collecting stages. For the EVs sector in particular, and due to the EU strict legislations, there is a high collecting rate of vehicles with all types including the electric vehicles (reaching around 87%) of the total end-of-life vehicles based on Eurostat database on end-of-life vehicles, consequently leading to the same collecting rates of Li-ions

used in EVs. The problem lies with the recycling processes of Li as a material. Although the Li-ions are re-used as secondary products, the material inside the batteries are replaced and thus leading to the use of virgin material to recover the whole battery. This process does not help the recovery of Li as an element.

Although new technologies can bring up recovery methods for Lithium as a material, policy makers should consider the focus on lithium recovery. The problem is that the importance of materials to the industries is the driving force for material recovery, such as cobalt and nickel. These metals are also contained in mobile Li-ion batteries, and are currently obtained from spent batteries due to their high value in the market where in the same time, Lithium recovery is not a priority (Wanger, 2011; Georgi-Maschler et al., 2012).

## 6 CONCLUSIONS

Natural resources have been the major source for providing the needs of global communities including food production, industrial production and others. The continuous rise in the global population and the economic growth leads to the growing consumption in different industrial sectors. Among the available natural resources, some of them are non-renewable, meaning that with this economic and population growth, there is a potential that these non-renewable natural resources will eventually become insufficient to meet the global demands. This situation has created the argument about critical raw materials (CRM), where scientists and researchers are working on identifying the assessment criteria for listing a raw material as critical or not. Most of the criticality assessment methods have introduced the supply risk as a predicting parameter for material criticality. In EU, a list of critical raw materials (CRM) was introduced based on two dimensional assessment method, including the supply risk and the economic importance as the two parameters to test the criticality of raw materials.

The aim of this study is to provide a comprehensive view on the critical raw material life cycle in the European Union. This comprehensive view includes the primary steps for obtaining raw materials passing by the processing, manufacturing, consumption and end of life stages of the materials, and goes further to the post consumption stages, where a detailed view on the fate of materials is presented, including, material recycling, landfilling or loss. In addition, this study provides a scenario based approach to determine the potential improvements on the lifecycle of materials in EU by modifying and improving the recycling activities.

Considering the dynamic behavior of systems, and the complex relationship and interdependencies between variables and parameters, system dynamics modeling is used as the methodological approach to achieve the goals of this study. The focus is on three critical raw materials, those are Phosphorus (P), Antimony (Sb) and Lithium (Li). Phosphorus and antimony have been already listed as CRM by the EU commission, whereas lithium has been a potential candidate in all consecutive reports by the EU commission. After deep literature review on the materials and a detailed creation of the materials life cycle for each one independently, the parameters affecting the system were taken into consideration, including growth factors, population growth, political decisions, legislations and restrictions. Those parameters were applied to the systems under study, which created the dynamic behavior of the systems through understanding and analyzing the complexities created.

## 6.1 Main Findings

The main findings correspond to the answers of the research questions formulated. For each material life cycle, the results were successfully obtained.

For phosphorus, the results of the study show that around 2336880 tonnes P enters the life cycle in EU. From this amount entering the P life cycle, around 962490 tonnes P is lost. The amount of the recycled material from waste streams to fertilizers is estimated to be 174694 tonnes P, whereas the amount landfilled is estimated to be 106616 tonnes P. Currently, 8.6% of material inside fertilizers is estimated to be originating from recycling activities. After improvements on recycling, 11.8%, 13.42% and 15.63% from the total amount of fertilizers are estimated to be originating from recycling by in 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> scenario respectively.

The amount of Sb entering the antimony life cycle in EU is estimated to be 37310 tonnes Sb, where 5130 tonnes Sb is lost. The estimations of annual recycled material in Lead-acid batteries sector shows an average of 3760 tonnes Sb, where the flow of landfilled material in the same sector is estimated to be 2024 tonnes Sb annually. The amount of recycled Sb in the Lead-acid batteries is estimated occupy around 27% of the total amount of Sb. The improvements on recycling rates increases this percentage to 30.23%, 33.24% and 36.14% in 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> scenario respectively. In the same life cycle, the annual amount of recycled Sb in other uses is estimated to be 3321 tonnes Sb, and the estimations of landfilled material is estimated to be 3050 tonnes Sb annually. The estimated amount of recycled Sb in other uses including textiles, PET and portable electronics is estimated to be 24% of the total amount of Sb. This percentage increases after improving recycling, reaching 26.55%, 29.54% and 32.3% in 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> scenario respectively.

The results estimations for the Li life cycle in EU shows that an average of 6189 tonnes Li enters the system annually, and that 1998 tonnes Sb is lost. In the Li-ion batteries sector, where lithium is significantly used, the amount of recycled material is 8.87 tonnes per year, which is considerably lower than the average annual landfilled material, which is estimated to be 880 tonnes Li. In the same sector, and with the current recycling activities for lithium in spent Li-ion batteries, the amount of recycled Li in Li-ion batteries is estimated to form 0.034% of the total amount of lithium in Li-ions. However, and with improving the recycling efficiencies though applying three different scenarios, this percentage increases, reaching 9.54%, 17.06% and 23.16 in the 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> scenario respectively.

## 6.2 Managerial implications

This research contains an overview of material flow in the EU, associated with numerical data and future estimations. Also, it is based on data collected from EU based sources, in addition to internationally recognized authentic databases. It provides clear view of the current situation of the CRM life cycle for EU managers. Further, the research opens up the question of potential improvements in the CRM's life cycle, not only in recycling, but in different stages as well.

Based on the results of each of the materials in this study, different implications can be drawn separately for each material. The different results for each material contributes to different management policies, and requires the focus on different life cycle stages. Generally, the EU policy makers are recommended to view the material life cycles from different angles and take decisions accordingly.

This research shows that the highest inefficiency for the P life cycle in EU occurs in the material lost throughout the life cycle stages. Regardless the loss from mining and processing stages, the major contribution to the material loss is the runoff of P from agricultural soils and the food waste. Also, results imply the necessity for applying policies on material loss especially on the solid waste stream that contributes to 78% of the total amount recycled. With food wastes being the main contributor to the solid waste stream, there is a potential to decrease the waste losses from food supply chain, and consequently from the whole P life cycle.

In addition, this research implies that a better management on the EOF material collection should be applied for Antimony life cycle in EU, especially in items including textiles, PE containers and portable electronics. Also, results show that reusing or recycling of products from this sector should be improved consequently. In another phase of products, particularly in the lead-acid batteries sector, attention should be drawn towards improving the recycling technologies for better recovery of Sb.

Further, the results of this research shows the importance of recycling in end-of-life products in the Li life cycle in EU. In the Li-ion batteries sector, new recycling technologies should be implemented to recover the amount of lithium inside these spent products, particularly those used in EVs. In the case of Li-ions used in portable devices (i.e. mobile phones), the possibility to recycle Li is reported to be hard and complicated to a significant level, hence,



increasing the collecting rates of spent Li-ions used in these types of products might not make sense from the material flow perspective, but may prevent possible environmental damages if collected.

### **6.3 Limitations**

The limitations associated with this research is related to the data availability of some product flows. In the Lithium life cycle, the tracking of material flow in some product sectors (i.e. glass& ceramics, lubricating greases, pharmaceuticals, and aluminum production) is not well established in this study. A clear view of the material flow to those sector could contribute to a better result and thus to more detailed managerial implications.

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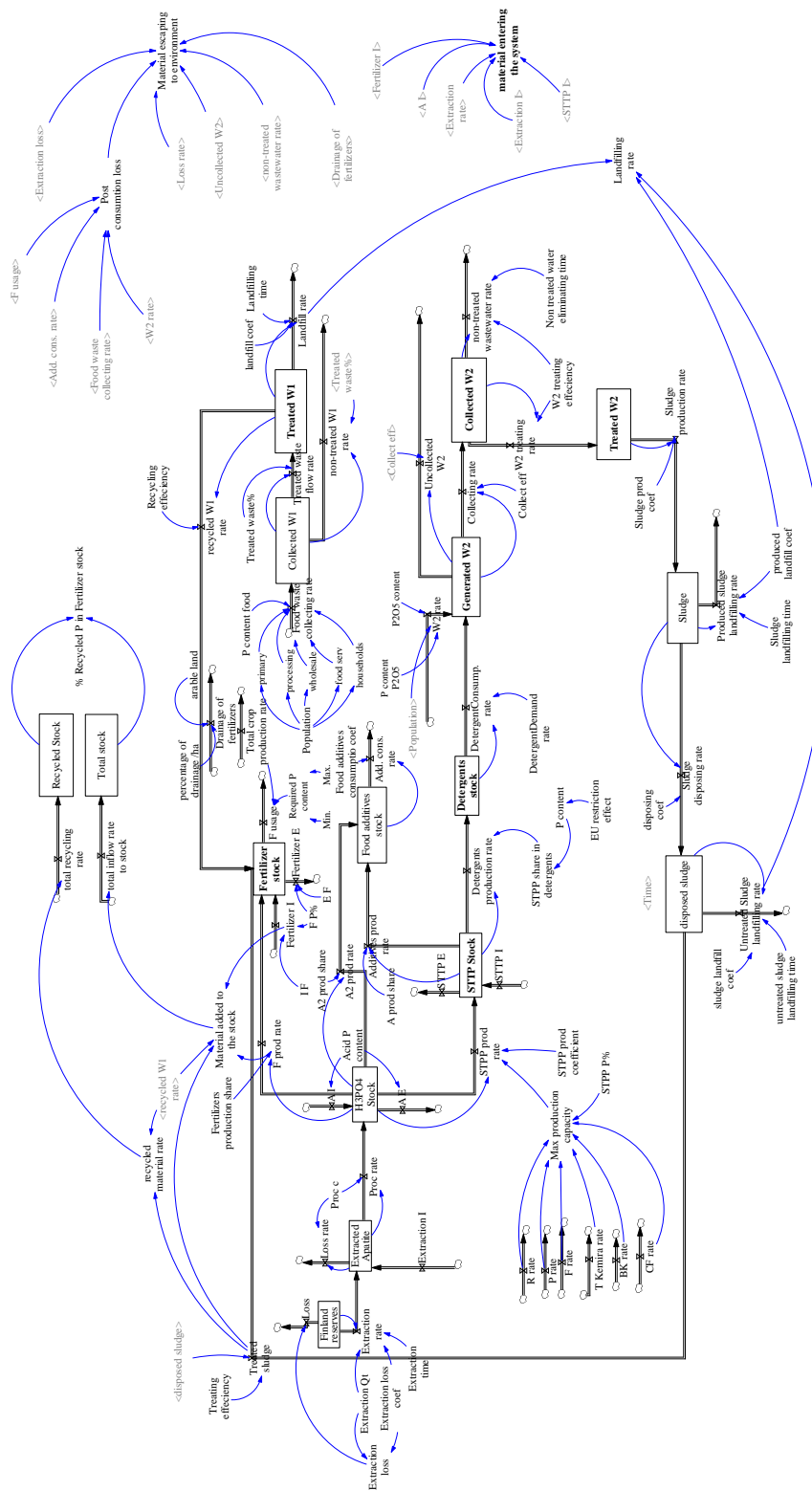
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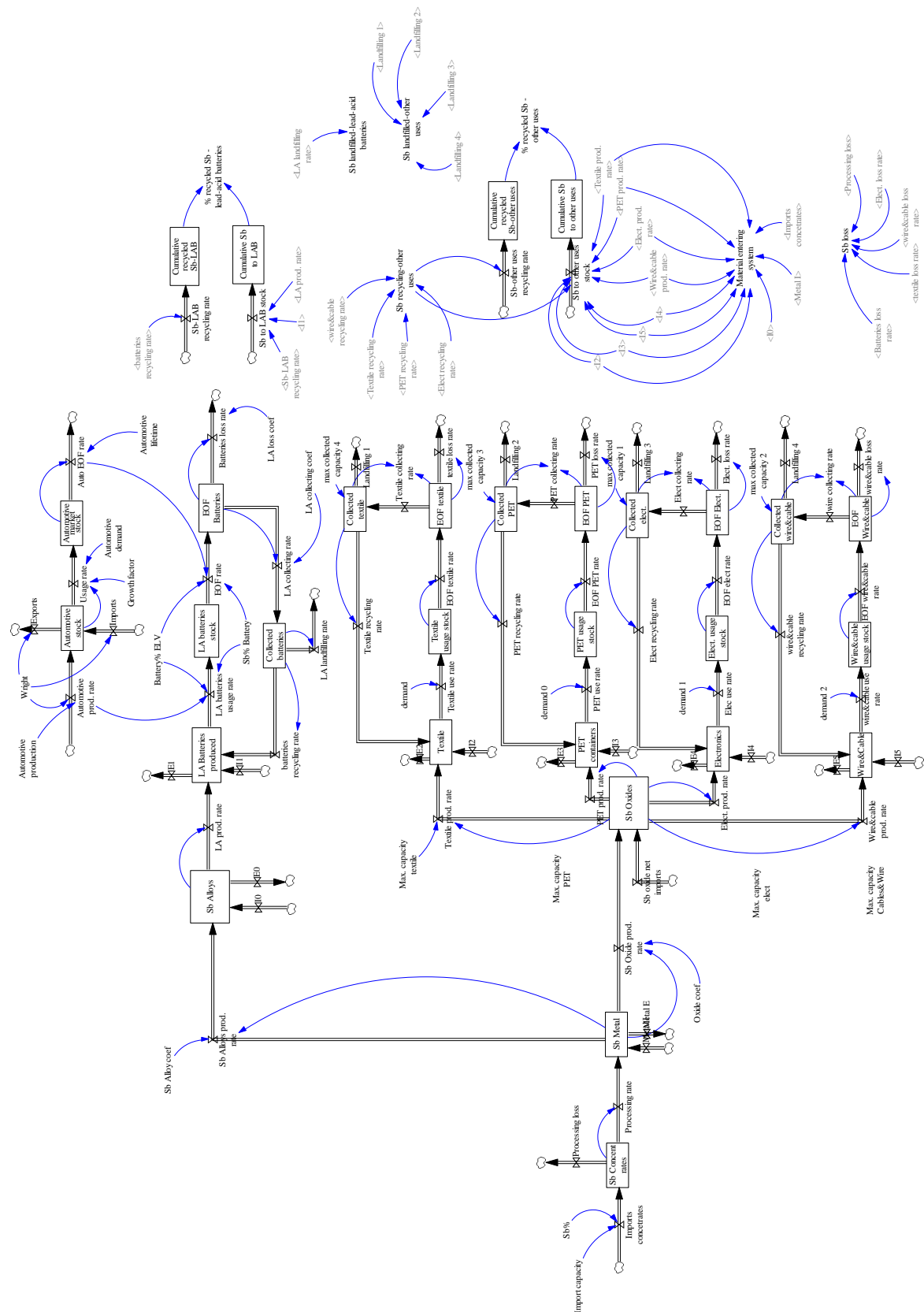
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## Appendix A System Dynamics model for the Phosphorus life cycle in EU



## Appendix B. System Dynamics model for the Antimony life cycle in EU



## Appendix C. System Dynamics model for the Lithium life cycle in EU

